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THE PETROLOGY
OF THE SEDIMENTARY ROCKS

THE

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OF THE

SEDIMENTARY ROCKS

A DESCRIPTION OF THE SEDIMENTS AND THEIR
METAMORPHIC DERIVATIVES

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PREFACE
TO THE SECOND EDITION

A SECOND edition of this book has been long overdue,
the first edition having been exhausted in 1919. The
war and its aftermath hindered the preparation and
publication of a revision. When at last it became
possible to proceed with the work, it was thought
desirable, both by the publishers and the authors,
that a complete revision should be undertaken. This
has been done, and· the accidental omissions· of the
first edition supplied. The appendix on " The System-
atic Examination of Loose Detrital Sediments," which
Mr. Crook was good enough to contribute to the first
edition, has been omitted, since there are now several
books dealing with the subject. But for this, the
additions now made would have added considerably
to the size, and consequently to the cost of the book.

The new matter includes *inter alia* sections on
the Influence of Climate on Sedimentation, on Chalk,

Crinoidal Limestone, Oolite, Marl, Brockram, Gyp-
sum, Radiolarian Chert, Loess, the Iron Ores of Lake
Superior and of Cumberland and Furness, the Potash
Deposits of Elsass and of Spain, and Crush-con-
glomerates. Several new figures, a considerable num-
ber of references to recently published work, and an
index of authors cited have been added.

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EXTRACT FROM THE PREFACE
TO THE FIRST EDITION

THE formation of the sedimentary accumulations and
of the rocks that result from their metamorphism,
embraces a complete cycle of changes. The insoluble
products of rock disintegration by the chemical and
mechanical agencies included under the head of
" weathering," furnish the material for the detrital
accumulations ; while the soluble products are either
precipitated (with or without the aid of organisms),
and thus form another class of sediment, or they
provide the cementing material for the already de-
posited sediments. But no sooner are the sediments
laid down than they begin to undergo change : thus,
they become consolidated under the weight of a
growing cover of later accumulations, or are cemented
by the deposition of new material from the waters
that circulate between their constituent grains. If
by the piling up above them of later deposits, the
earliest accumulations are depressed to regions of

high temperature and pressure, a severer type of metamorphism comes into play; and the rise of the isogeotherms will bring about baking and corrosion by magmatic vapours, while pressure and orogenic movements will entail cleavage and deformation.

Any of the rocks thus produced are liable to be again broken down should they, either by orogenic elevation or by denudation, be brought into the zone of weathering; and with the deposition of the new products of disintegration a fresh cycle of changes is started. Resistant minerals, such, for example, as zircon, rutile, and garnet, have no doubt survived many such cycles of change before reaching the positions in which they are now found.

The study of the sediments therefore embraces not only loose detrital accumulations, but also their derivatives by cementation, metasomatism, and other forms of metamorphism; and the present volume is accordingly divided into two parts, the first of which deals with the SEDIMENTS and the second with their METAMORPHIC DERIVATIVES.

The sedimentary rocks have, in comparison with the igneous rocks, been neglected by petrologists, although they are from all points of view not one whit less interesting. Even such observations as have been made on their occurrence, petrogenesis, microscopic structure, and composition are scattered through

the Transactions of Societies and similar publications ; and there has been, as yet, no serious attempt to systematise them and to make them available for the student in the form of a text-book. This the authors of the present volume have set out to do.

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PART I

THE SEDIMENTS

CHAPTER I

DEPOSITION IN GENERAL

THE fundamental principle upon which the treatment of our subject is based is that of CONTINUITY; this principle forming a natural part of the Uniformitarian doctrine of Hutton and Lyell and teaching that the sedimentary portion of the solid crust of the earth was deposited by the ordinary geological agents, namely, gravity, wind, running water, ice, marine action, and so forth, with which we are familiar at the present day. The various processes of consolidation, cementation, metasomatism, and other forms of metamorphism, often mask the original character of the older deposits; but comparison with some modern type is generally possible. No doubt there exist among the older rocks types that have been formed by processes not exactly similar to any now in operation; but some analogy can always be found, and the principle may be said to hold good universally. Many of the older sediments indeed possess characters so similar to those of modern deposits that we can determine with certainty the conditions under which they were formed. Where fossil remains exist such

determinations are greatly facilitated; but even totally unfossiliferous rocks can in many cases be assigned with certainty to their proper class. There are rocks, however, that have undergone such intense alteration by heat and pressure that the question whether they are of igneous or of sedimentary origin is incapable of solution (see p. 273).

Definition of the Term Sediment. — The word sediment in its ordinary interpretation signifies solid material that has settled down from a state of suspension in a liquid. As used in this book, however, it includes not only all rocks formed by the settling down of solid material in water, or by chemical or organic agency, but also many deposits in the formation of which water takes no part, *e.g.* desert sands and wind-borne material generally. Glacial deposits of all kinds are included, and, in short, all rocks not directly of igneous origin. But many ancient and modern deposits, though true sediments, contain a good deal of material derived from explosive volcanic action but which has been mixed with normal sedimentary material in lakes or in the sea, and it is therefore difficult to draw any definite line between the volcanic ashes and the sedimentary rocks.

Facies of Deposition.—It would be outside the scope of this work to give a full account of the geological processes of disintegration and transport that provide the materials for the sedimentary deposits. These come under the general heading of *denudation*, one of the most important subdivisions of physical

geology. We are concerned here less with the mode of action of these processes than with their results ; and the study of denudation is important for us only in so far as it affects the character and ultimate destination of the material. It is usually easy to distinguish between denudation and deposition, which commonly stand to one another in the relation of cause and effect ; but in some cases the two processes are so closely associated that it is very difficult or even impossible to distinguish them. This applies to almost all forms of terrestrial accumulation, and to a considerable extent also to marine deposition in shallow water within reach of wave-action. In the depths of the sea, on the other hand, and in lakes, denudation is at a minimum, and there it is possible to study deposition without disturbing factors. The great majority of the sediments, and especially those that conform most closely to the strict meaning of the term, are formed directly from the material of pre-existing rocks, and may be distinguished as *fragmental* sediments. Others, however, that are produced for the most part by physico-chemical processes, such as *precipitation* and *evaporation*, or as the result of the activity of animals and plants, can only be regarded as derived indirectly from older rocks, since the material has been deposited from solution, as in the case of coral-limestone and rock-salt.

A very slight acquaintance with the principles of geology suffices to show that under similar conditions similar deposits are formed. The term *similar*

conditions must, however, be interpreted as a function
of two independent variables. One of these is the
actual physical environment of the area where deposi-
tion takes place, which may be marine, fresh-water,
or terrestrial; the other is the nature of. the material
supplied. Obviously the deposits arising from the
weathering, disintegration, and transport of a granite
will be different from those yielded by a limestone
under similar influences ; and this consideration is
evidently of great importance in determining the
chemical and mineralogical composition of the result-
ing deposit. In general terms it may be said that
local conditions are of the utmost importance in
determining the *physical characters* of a deposit, *i.e.*
its state of division and its organic content ; while
the source of the material largely determines its
mineralogical composition.

Under a given set of conditions deposits of a certain
general type tend to be formed ; and the relationship
between these and the conditions under which they
were formed is summed up in the general term *facies*,[1]
this term being used to connote the sum of the litho-
logical and palæontological characters exhibited by
a deposit. Two contemporaneous formations of the
same facies are said to be *isopic* ; when of different
facies they are *heteropic*. Examples of formations
presenting the same facies over wide areas are the
graptolitic shales of the Lower Palæozoic systems, the
Lower Lias, the Greensands of the Cretaceous, the

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[1] See Haug, *Traité de Géologie*, vol. i, pp. 144-56.

Nummulitic limestone (Eocene), and the modern Globigerina ooze. But almost every formation, when traced over a sufficiently wide area, is found to pass laterally into rocks of a different lithological type, yet containing some of the same fossils and therefore contemporaneous. Thus graptolitic shales are represented in other regions by thick beds of shelly grit or by limestone, and the Eocene beds of Britain are very different from the contemporary limestones of the Mediterranean basin. The Devonian rocks and the Old Red Sandstone, though contemporaneous in a broad sense, are very different, and the Chalk of north-western Europe is represented in southern Europe by the Hippurite or Rudistes limestone. Each of the formations just quoted exhibits two very different facies, controlled for the most part by the conditions of formation. Thus we know from the contained fossils that the Devonian rocks are of marine origin, while the Old Red Sandstone is a continental type, and a similar relation holds good in many other cases.

The following table shows in a condensed form the chief facies which can be recognised :

MARINE	.	.	.	Shore facies.
				Shallow-water facies.
				Deep-water facies.
				Abyssal facies.
CONTINENTAL	.	.	.	Alluvial facies.
				Lacustrine facies.
				Glacial facies.
				Æolian facies.

In addition there are the ESTUARINE DEPOSITS,

which form an intermediate class between these two great groups. The salt-lake deposits and certain masses of calcium carbonate and silica (sinter and travertine) are strictly continental in origin. Lastly, the semi-volcanic fragmental deposits, before alluded to, may be formed either on land or in water.

The Influence of Climate on Sedimentation.— From what has been already said it is clear that the deposition of sediment is for the most part due to natural agencies, such as gravity, wind, ice, rivers, tides, waves, and currents, and the vital activities of animals and plants, most of which are influenced to a greater or less extent by meteorological conditions. Hence it is evident that the sum of these conditions, or climate, must have an important influence on the type of sedimentation. From this point of view the earth as a whole can be divided into zones, which run more or less parallel to the equator. In the tropical zone the prevailing conditions are dampness and high temperature, both of which favour chemical and bacterial action. Hence the minerals of pre-existing rocks are rapidly decomposed and the secondary compounds formed are, as a rule, simple and highly oxidised. Also, since the rank tropical vegetation characteristic of this zone prevents any rapid removal of the decomposed rock, residual deposits accumulate to a great depth. Next to the tropical belt comes the hot dry desert belt, lying in the trade-wind region, where water action is almost non-existent and the chief agent of transport is wind. Here the rocks are

disintegrated mainly by the shattering action of rapid changes of temperature and there is very little chemical change. In consequence great masses of scree material and wind-rounded sand accumulate. Organic deposits are completely absent in this zone. In still higher latitudes come the temperate zones, where seasonal contrast is great and nearly all the familiar agents of denudation and deposition come into action. In the colder parts of the temperate zone frost action is of great importance in winter, and at all seasons organic agencies play a part. Finally, in the arctic regions there is, as a rule, no running water, and the effects of snow and ice are dominant : so far as sedimentation is concerned these regions may be regarded as dry.

The climatic conditions of the different zones may be conveniently summed up as follows :

Arctic zones .	.	.	.	Cold and dry.
Temperate zones .	.	.	Cool and damp.
Desert zones.	.	.	.	Hot and dry.
Tropical zone	.	.	.	Hot and damp.

These different zones obviously possess no sharp boundaries, but grade insensibly into one another ; furthermore, increase of altitude acts similarly to increase of latitude : high land in the tropics must possess a temperate or even an arctic climate. It is hardly necessary to enlarge here on the well-known and striking climatic variations produced by hot and cold ocean currents and prevailing winds in places situated in similar latitudes : all these factors have, however, to be

taken into account in considering the types of sedimentation now in progress or prevailing in past geological times. A careful study of the older deposits often leads to definite conclusions as to the climates of the past, and some particularly interesting facts have thus been established as to the former existence of glacial conditions in low latitudes, while it is clear that typical desert conditions have prevailed even in the far north over vast areas and at many different periods of time.

Marine Deposition. — In some respects marine deposits are the most important of all, and they are often regarded as the typical sediments. That the marine sediments have received more attention at the hands of geologists is, however, to be attributed partly to the fact that they are frequently highly fossiliferous, and partly to the temporary nature of terrestrial sediments, which only mark halting stages on the road to the sea.

The conditions that prevail in the sea vary within very wide limits, and the character of the deposits formed is intimately connected with them. Perhaps the most important factors are depth and distance from land ; and, other things being equal, the character of the deposits (and especially the size of their constituent particles) is controlled by these. Other important factors are the nature and amount of the material supplied from the land, the extent to which life has been developed in the sea, and the prevailing climatic conditions.

The material derived from the land either by the ordinary processes of denudation, combined with river-transport, or by coast-erosion is distributed on the sea bottom by waves, tides, and currents. Besides fragmental materials of inorganic nature, it consists of shells and other calcareous and chitinous structures of animal origin derived both from the land, where they may have existed as fossils or be of recent origin, and from marine life in being at the time of deposition. Many marine deposits are even of direct organic origin, being built up by the vital activity of animals and plants from substances dissolved in sea-water ; such, for example, are the coral-reefs of tropical seas. In the deepest parts of the ocean, far from land, the deposits have a special character, being largely formed from the planktonic organisms. Another notable source of the fragmental material of the marine sediments is wind-borne dust or the ash from volcanic explosions.

The distribution of marine deposits is greatly influenced by the general form of the oceanic basins. Off the coasts of many land-masses the submarine slopes are very gentle near the land ; but at a certain determinate depth, usually about 100 fathoms, there is a sudden increase in the steepness, and thereafter great depths are rapidly attained. The true boundary between the continents and the ocean basins is therefore not at the shore-line, but at or about the 100-fathom line ; and the area between the actual shore and the 100-fathom line is regarded as belonging to

the continents, though at present overflowed by the
sea. This area, known as the *continental shelf*, is in
some parts of the world of very considerable extent.
Its existence is specially noticeable off the coasts of
north-western Europe, where, excepting a narrow,
deep channel off Norway, it embraces the whole of
the North Sea. A broad zone of shallow water also
exists off the eastern coast of the United States and
South America. This frequent existence of a broad
expanse of comparatively shallow water determines a
widespread distribution of shallow-water sediments.

According to the classification of marine sedi-
mentary deposits here adopted, the oceanic areas may
be divided into four regions or zones, as follows :

> 1. Shore zone.
> 2. Shallow-water zone.
> 3. Deep-water zone.
> 4. Abyssal zone.

1. The *shore zone* comprises the region between
high and low water mark, together with a higher-
lying strip which is subject to wave-action during
storms. It embraces, in other words, what is popu-
larly known as *the beach*.

2. The *shallow-water zone* includes the whole area
of the continental shelf, as above defined ; it there-
fore ranges from low-water mark to the 100-fathom
line.

3. The *deep-water zone* extends from the edge of
the continental shelf down to a depth of about 1500
fathoms. The latter figure is somewhat arbitrary,

but it is approximately the greatest depth to which material derived directly from the land ever reaches.

4. The *abyssal zone* comprises everything beyond the deep-water zone and occupies the greatest area of all.

Each of these zones is characterised by a special kind of sediment, whose character is determined largely by the state of division of the particles, this being itself dependent on the distance from land; thus the characteristic sediment of the SHORE ZONE comprises boulders, pebbles, and coarse sand; that of the SHALLOW-WATER ZONE, fine sand and organic deposits; while that of the DEEP-WATER ZONE is mud, and that of the ABYSSAL ZONE, ooze.

This table affords the basis for a classification of marine deposits of very wide application, and in the main capable of extension to the great majority of sediments formed, under other conditions, in fresh water and on land.

Estuarine and Lagoon Deposition. — The sediments laid down in the estuaries of large rivers resemble in many respects those of the open sea, but have certain distinctive features. Being to a certain extent intermediate between marine and fresh-water deposits, they possess some of the characters of both. Their organic contents generally are a mixture ·of marine and fresh-water or terrestrial forms; and plant-remains are usually abundant. Lithologically, they are often characterised by the prevalence of mud in much shallower water than is usual on an open coast.

This mud, which often exists to an enormous extent
between tide marks, is, of course, formed by the
accumulation of the fine silt brought down in a state
of suspension by the rivers and precipitated by the
coagulating effect of the salts dissolved in sea-water.
Pebble and sand beds are abundant, but calcareous
deposits rare or absent, owing to the fact that muddy
water is unfavourable to the growth of animals and
plants that build up massive calcareous skeletons.
One of the noteworthy features of estuarine deposits
is a rapid alternation of different types of sediment,
often in very thin layers. This is due, no doubt, to
the variation in the amount of material brought down
by the rivers, and in the size of its component particles,
the result, in both cases, of changes in the supply,
arising from the alternation of periods of low and high
water. Very closely connected with this class also
are the delta deposits of some large rivers, such as
the Rhine, Nile, and Mississippi ; but these show a
still closer relationship to the alluvium of the land :
they are perhaps best regarded as forms transitional
between estuarine and terrestrial deposits.

Lagoons.—Some coast-lines are bordered by areas
of shallow water, separated from the open sea by
barriers of sand or coral-reef.[1] Such lagoons originate
in many different ways ; sometimes the formation
of pebble-banks and sand-spits cuts off inlets of the
sea, sometimes barrier-reefs of coral-rock are formed,

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[1] Dixon and Vaughan, " The Carboniferous Succession in
Gower," *Quart. Journ. Geol. Soc.*, vol. lxvii, 1911, pp. 512-32.

etc. In consequence of this great diversity of origin very various conditions prevail. The lagoons of tropical regions show a rich vegetation, as in mangrove swamps; while the intense evaporation that prevails in regions of high temperature may give rise to salt and gypsum deposits. Lagoons enclosed by coral-reefs teem with life and produce richly fossiliferous, calcareous deposits, and it seems to be reasonably certain that many coal seams were formed under lagoon conditions.

Continental Deposition. — The term *continental* is here interpreted in its widest sense, so as to include all the deposits formed on land-areas, whether freshwater or strictly terrestrial. Lakes must be regarded as portions of the hydrosphere which, owing to special causes, have become isolated; and the river-systems of the land clearly appertain to the continents. There are also many deposits in the formation of which water plays little or no part, such as the blown sands of desert regions and of many coasts; while the glacial accumulations of high mountain ranges and of the Arctic zones constitute a special class, in the formation of which ice plays the chief part. Hence four principal facies of continental deposition may be distinguished, viz. *alluvial*, *lacustrine*, *glacial*, and *æolian*.

The term *alluvium* in its strict sense connotes any solid material transported by fresh water and subsequently deposited; hence it may be used to describe in general terms the great class of accumulations that owe their origin to the agency of running water, and

especially those masses of solid material that are trans-
ported from higher to lower levels by rivers. Deltas
belong for the most part to this group, although some-
times these contain an admixture of matter derived
from the sea. Much true alluvium is also formed in
lakes. Its accumulation may even be continued until
the lake is obliterated and replaced by alluvial flats,
over which rivers meander. There is, therefore, a
very close connection between the alluvial and lacus-
trine facies. On the other hand, much of the alluvium
formed on actual land-surfaces is essentially *soil* and
rain-wash. Other alluvial accumulations are the cones
and stream-deltas of mountain regions, and also screes
and mud-flows. (In short, the alluvial or running-
water facies includes all the accumulations formed
on the land-surface where there is a well-developed
drainage system, in so far as such accumulations are
not referable to ice or wind action, nor are due to
chemical or organic causes.) An exception must be
made in regard to deposits in lakes of considerable
size. Large lakes of fresh water show phenomena of
denudation and deposition exactly comparable to those
observed in the sea, and similar littoral, shallow-water,
and deep-water phases exist. In the smaller lakes,
however, only the shore and shallow-water zones are
represented. In some lakes organic accumulations are
predominant, the final result of alluviation in some
cases being an extensive development of peat.

(In salt lakes totally different conditions prevail.
These lakes possess no outlet, and the only means

of removal of water is by evaporation. Consequently all material brought in by rivers must remain in the lake, and the concentration of the dissolved substances gives rise to extensive chemical deposits.) Salt lakes are commonly related to desert conditions, and, strictly speaking, belong to the terrestrial facies, which may be taken to include both salt-lake and wind-borne deposits.

Glacial accumulations constitute a well-marked class, distinguished both by topographical forms and by the character and distribution of their components. (The most characteristic of all the products of glaciation is *boulder-clay*, although glaciers also give rise to sand and gravel deposits, which are sometimes difficult to distinguish from those laid down by rivers. Since such deposits are formed for the most part by the streams resulting from the melting of ice, they are commonly designated *fluvio-glacial*. Transport by floating masses of land-ice plays an important rôle in some parts of the world, especially in the regions bordering the great ice-caps of the Arctic and Antarctic ; also in the rivers of North America and Siberia.

Æolian Deposits.—Transport by wind prevails most largely in regions of deficient rainfall, that is, under desert conditions. In more temperate climates wind-action is of importance only under special conditions, as for instance along sea-coasts open to a prevailing wind. Here sand cast up by the waves is often carried landwards in great quantities, and forms extensive sand-hills (dunes). In some inland districts,

even where there is a fairly heavy rainfall, if the soil
happens to be specially sandy, wind-transport is an
important factor.

In true desert regions wind is the only agent of
transport and deposition other than gravity, and by
its action a special type both of topography and of
deposit is produced. Desert regions are always
marked by an almost complete absence of animal and
vegetable life. Where a fauna and flora exist, they
are scanty, and present special peculiarities of structure
arising directly from the influence of their environ-
ment. The close association of wind-blown accumu-
lations with beds of rock-salt, gypsum, and other
minerals formed by evaporation of salt lakes has
already been noted.

Classification of Deposits.—Although theoretically
excellent, the classification we have been discussing
presents difficulties when applied to existing sediments,
for the simple reason that very similar deposits are
formed under varying conditions. A strict applica-
tion of the method would involve much needless
repetition, and it is therefore more convenient to
group together all similar sediments under a general
heading. In this way a classification can be con-
structed on lithological lines, partly physical, partly
chemical and mineralogical, as has been done in the
case of the igneous rocks.

The sediments, however, show variations between
much wider limits than do the igneous rocks, and
their classification is consequently less definite and

precise. The large class of FRAGMENTAL DEPOSITS is of purely mechanical origin ; the chemical and mineralogical composition of these may vary very widely, but a certain state of division of the particles is commonly associated with definite physical conditions. Thus, if we take marine sediments as a type, it is found that shore accumulations consist largely of *boulders* and *pebbles* : under shallow-water conditions *sand* is deposited, and in deep-water, *mud*. Here, then, we have four lithological types to which a vast number of deposits of other than marine origin can be assimilated. It is true that these terms are somewhat vague and ill-defined, but they have a well-known popular meaning, and there need never be any doubt as to their general significance.

The next group, the CHEMICAL DEPOSITS, includes all accumulations formed directly by evaporation of solutions, or occasionally perhaps by the formation of insoluble precipitates on mixing solutions of two soluble salts. The most important natural substances deposited in these ways are calcium carbonate and the salts contained in sea-water (chiefly chlorides and sulphates). The naturally occurring nitrates and borates are also included in this group. The deposits of colloid silica left by hot springs may also belong here, although their formation is possibly due in large measure to organic agency.

The remaining group—the ORGANIC DEPOSITS— includes deposits the origin of which can be traced directly to the vital activity of animals and plants.

Its most important subdivisions are the *calcareous* and the *carbonaceous*. The first‑named includes the majority of the marine organic deposits, together with a certain number formed in fresh water. The carbonaceous deposits of the present day include those formed by the decay of vegetable matter under certain anærobic conditions, probably through the medium of bacteria, while many modern *ferruginous* deposits owe their origin to plant life, possibly also of a bacterial nature.

The abyssal deposits are partly organic (plank‑tonic) and partly of a muddy nature. Their diversity of origin, and the fact that they are not known to exist among the older altered sediments, make their treatment in a special section desirable.

The following classification of modern sediments is drawn up in accordance with the general principles stated above :

FRAGMENTAL
- Boulder and scree deposits.
- Pebble deposits.
- Sand deposits.
- Dust and mud deposits.

CHEMICAL
- Chloride deposits.
- Sulphate deposits.
- Borate deposits.
- Nitrate deposits.
- Carbonate deposits.
- Silica deposits.

ORGANIC
- Calcareous deposits.
- Ferruginous deposits.
- Carbonaceous deposits.

CHAPTER II

FRAGMENTAL DEPOSITS

IN accordance with the scheme of classification out-
lined in the preceding chapter, *fragmental deposits*
include all those accumulations of material, either
residual or transported, that have been formed by the
disintegration under the influence of the weather of
pre-existing rocks. Since the fragments, thus pro-
duced, may be of any size whatever, it is necessary to
classify the deposits according to the size of their
components, namely, as *boulders*, *pebbles*, *sand*, *dust*,
and *mud*.

Boulder and Scree Deposits.—Under this heading
we propose to include all those deposits, however
formed, in which the size of the majority of the com-
ponents exceeds 10 centimetres. To those ·in which
the fragments are rounded the term *boulder deposit* is
applied ; while for those composed of angular frag-
ments we have adopted the term *scree deposit*, the word
" scree " being commonly used to describe the frag-
mental material that collects on steep mountain slopes.
Since the distinction depends solely on form, there is
complete transition between the two groups. Boulder

and scree deposits are formed in a great variety of
ways, but in all cases their formation is dominated
by continental conditions.

Boulder Deposits.—(These are found on the sea-
shore, in rivers and lakes, or on dry land ; while in
respect of origin they may be residual, or they may
be transported. Perhaps the simplest form are the
residual deposits resulting from the disintegration in
place of older rocks, either igneous or sedimentary, in
which for some reason the intensity of the weathering
has varied in different parts.) In the case of a deposit
like boulder-clay the reason for this is obvious : it
consists of blocks of hard rock embedded in a soft
matrix ; the removal of the latter causes the hard
blocks to accumulate, as on the beaches of the York-
shire coast. Many of the older conglomerates possess
a somewhat soft matrix or cement, so that the com-
ponent pebbles are easily set free. This occurs, for
instance, in the Old Red conglomerate of Scotland,
which is often very coarse in texture. (Concretions of
harder material in soft sedimentary rocks are often
left behind as a boulder deposit. Such concretions
are commonly of calcium carbonate or of compounds
of iron ;) but concretionary nodules of phosphates and
manganese compounds are not uncommon. Quartz
veins traversing soft strata also give rise to residual
boulder deposits.

(Among such residual deposits must also be classed
the *boulders of disintegration*[1] that are formed by the

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[1] Branner, *Bull. Geol. Soc. Amer.*, vol. vii, 1896, p. 269.

breaking up of igneous rocks along joints, a process which is accompanied by a rounding of edges and corners by weathering. Tumultuously heaped masses of huge boulders and partially rounded blocks are specially characteristic of countries where there are great diurnal variations of temperature; the granite kopjes of Mashonaland and the dolerite kopjes of the Karroo in South Africa are familiar examples. Very similar in origin are the granite tors of Devon and Cornwall, and the great masses of shattered rock that form the summits of many of the higher mountains of the British Isles.

Transported deposits of coarse material are very abundant; their origin may be attributed to gravity alone, or to the action of waves, of running water, or of ice.

In the case of boulder deposits formed by *running water*, the weight of the transported fragments is proportional to the sixth power of the mean velocity of the current,[1] and it follows that small streams with a steep grade can transport very large blocks, especially during floods; hence these accumulations come under the general heading of *torrential deposits*, and they are found for the most part in upland regions; sometimes, however, when a river has a rapid fall throughout its whole length, they may even extend down to sea-level. In mountain regions the rock fragments of torrential deposits are of very large size, and often weigh several tons each. They are usually very well rounded, except

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[1] Hopkins, *Quart. Journ. Geol. Soc.*, vol. viii, 1852, p. 27.

in the highest parts of the stream near its source.)
Occasionally continued gyration in a pot-hole produces
extraordinarily perfect spheroidal forms.

(Boulder deposits are formed by all rapid streams,
and usually occur on a great scale in upland valleys
and at the foot of mountain slopes.) Examples of both
ancient and modern date are extremely abundant in all
parts of the world. In Britain they are well developed
in Wales, in the Lake District, and in Scotland.
Similar deposits also occur on a very large scale in
South Africa, at the foot of the Langebergen and other
mountain ranges of Cape Colony, and in the gorges of
the rivers that cut through these ranges.[1] The blocks
of Table Mountain sandstone and other hard rocks are
sometimes very large, up to 5 or 6 feet in diameter, and
the thickness and wide distribution of these deposits
are to be attributed to the action of violent floods such
as prevail in these regions. The Enon conglomerate,
of Cretaceous age, which is found in the same district,
was obviously formed in a similar manner and under
similar conditions ; when weathered it is hard to dis-
tinguish it from the recent and sub-recent boulder
deposits just mentioned.[2]

The rounding of the boulders in these deposits
does not always result from attrition in water alone.
Streams sometimes obtain their blocks from pre-

[1] Rogers and du Toit, *Geology of Cape Colony*, 2nd edition,
1909, p. 372.
[2] Rastall, " The Geology of the Districts of Worcester,
Robertson, and Ashton, Cape Colony," *Quart. Journ. Geol. Soc.*,
vol. lxvii, 1911, p. 719.

existing deposits in which they were already well rounded ; and doubtless boulders are often passed on from one deposit to another with but little change. This subject will be discussed more fully later (see p. 32).

Ice in all its forms is a potent agent in originating boulder deposits. Modern glacial deposits are of course confined to high altitudes or high latitudes, but in the earlier part of the Pleistocene period glacial conditions extended far and wide over parts of Europe and America that are now temperate ; and we have clear evidence of the former existence of glacial conditions in low latitudes in India and in the southern hemisphere. The most characteristic of all products of glaciation is boulder-clay, which in its most typical form is a stiff clay with a varying proportion of rock-boulders. The latter are commonly angular and have often been faceted or striated by attrition on rock surfaces, or by mutual pressure. Boulder-clay sometimes contains intercalated beds of sand and gravel, and thus grades into fluvio-glacial deposits. No true boulder-clay is now being formed by the glaciers of the Alps, or, so far as is known, by any glaciers of the valley or Alpine type. To find true modern boulder-clay we must turn to Greenland, Spitsbergen, or the Antarctic, where it seems to be a characteristic product of glaciation by continental ice-sheets. Boulder-clay is largely developed in Britain north of a line joining London and Bristol, and it is also very abundant in North Germany, Holland, and the United States. As

British examples the boulder-clays of the Yorkshire coast may be quoted ; these consist of an exceedingly stiff and tenacious red clay, in which are embedded numerous angular, subangular, and rounded boulders whose derivation from Scandinavia, Scotland, and the Lake District is easily recognisable. These boulders are frequently of one or two tons weight, and sometimes even more.[1] The Cromer Till of Norfolk is another example. The Great Chalky Boulder-clay, that covers so much of central and eastern England, is somewhat lighter in character, since it contains a large proportion of ground-up Chalk : its boulders are of British origin, except where derived from older boulder-clays.[2]

Perhaps the most abundant of all glacial deposits, especially in mountain regions, are those to which the general term *moraine* is applied. Moraines consist of irregular accumulations of fragmental material, a marked feature being the indiscriminate admixture of blocks of all sizes ; this is due to the fact that there can have been no sorting action, as in water deposition. The blocks are commonly angular and often striated ; in fact, moraine material resembles the coarser constituents of boulder-clay, without the argillaceous matrix.

Very closely related to moraines are *fluvio-glacial* deposits, which consist of moraine material sorted

[1] A block of Shap granite found at Seamer, near Scarborough, is 9 feet high.
[2] Hill, "On the Matrix of the Suffolk Chalky Boulder-Clay," *Quart. Journ. Geol. Soc.*, vol. lviii, 1902, p. 179.

and re-deposited by running water. Here there has been usually a certain amount of grading according to size, and sometimes a rough stratification may be observed, although this is more characteristic of the finer material. Fluvio-glacial deposits are with difficulty distinguishable from ordinary torrential boulder deposits; but the inclusion of far-travelled blocks sometimes affords a useful index to their origin. Thus the fluvio-glacial gravels of the valley of the Thames contain, besides Bunter pebbles, sandstone, quartzite, tourmaline-breccia, quartz-schist, and rhyolite.[1] It is perhaps worth noticing here that the so-called *anchor-ice* of northern rivers often transports large boulders, and mixes them with other deposits either lower down the river or even in the sea. A similar process is the carrying of large quantities of material over the sea by floating icebergs derived from the land. This certainly accounts for many of the large boulders found in marine sediments; and in the Arctic and Antarctic regions it gives rise to a peculiar type of oceanic deposit. The total amount of material carried south by icebergs and dropped on the banks of Newfoundland, for example, must be enormous, and a similar process probably accounts for the presence of abundant large boulders of distant origin in the Cambridge Greensand.[2]

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[1] Sherlock and Noble, "On the Glacial Origin of the Clay-with-flints of Bucks," *Quart. Journ. Geol. Soc.*, vol. lxviii, 1912, p. 204.

[2] Sollas and Jukes-Browne, "On the included Rock-fragments of the Cambridge Upper Greensand," *Quart. Journ. Geol. Soc.*, vol. xxix, 1873, p. 11.

Instances are known in the far north where ice laden with boulders is driven on to the shore, or forced through a narrow channel, and both of these causes may result in the formation of boulder terraces along the coast.

Turning now to *marine deposition by wave-action* alone, uncomplicated by ice, we find the conditions fairly simple. Most of the larger blocks coming under our definition as to size must be obtained more or less locally : only in exceptional cases can large boulders be transported far. Usually they are the result of the denudation of the coast, and their form and degree of rounding must obviously depend on many causes, the most important of which are the state of the fragment when separated from the parent rock and the amount of abrasion it has since undergone. Here, as elsewhere, boulders may be obtained ready-made from an older conglomerate. One of the most notable features of all beach deposits is the amount of sorting by wave-action undergone by the fragments, so that on many beaches there is a regular gradation from boulders at the foot of the cliffs, through pebbles, to sand at and below low-water mark. Deposits coming within the limit of size here adopted are usually found above high-water mark, to which only the storm-waves ever reach. At the foot of steep cliffs the accumulations are to a large extent of the nature of screes, but the material soon becomes rounded if within reach of wave-action. Deposits of this kind are so common that it is quite unnecessary to mention special examples.

Scree Deposits.—The screes of mountain regions consist of blocks of rock of all sizes and shapes that have been loosened by weathering and have fallen or slipped by their own weight. In cold regions the scree material owes its origin to the expansion of water on freezing in the joints of rocks. This phenomenon is operative in the arctic zones and in the mountains and hills of temperate latitudes, and, of course, in the highest parts of high mountains in all parts of the world : screes are therefore formed in all these places. In Britain the screes of Wastwater, in the western part of the Lake District, are very well known. They rise to a height of about 1500 feet above the lake in one continuous slope at an angle of about 30°. Well known, too, are the light-coloured screes on the slopes of the Dolomites in the Tirol, which from a distance and in photographs look like patches of snow.

In regions where great extremes of temperature occur in the course of a day, the chief agent in scree formation is the sudden expansion and contraction of the rock, the unequal stresses thus set up causing fractures. Screes are therefore very highly developed on steep hills and mountain ranges under desert conditions, and excellent examples can be seen in the deserts of Egypt, the Sinai Peninsula,[1] and in many other hot and dry regions of the world. Under these conditions scree formation is much aided by a peculiar type of spheroidal weathering, for which Richthofen

[1] Walther, *Die Denudation in der libyschen Wüste.* See also *Das Gesetz der Wüstenbildung*, Berlin, 1900.

employed the term *desquamation.*[1] A notable feature of desert screes is, very commonly, the perfect fresh-ness of the material, since chemical weathering is in abeyance, except under special circumstances.

Pebble Deposits. — Under this heading are in-cluded all accumulations to which the popular terms gravel and shingle can be applied, together with some other fragmental deposits which can scarcely be so designated. Any limit of size which may be fixed for the components of a gravel must evidently be purely arbitrary : the figures here adopted are as follows. The minimum size of a boulder has already been defined as 10 centimetres : this gives the maximum for a pebble. For the lower limit of the pebble class we adopt a diameter of 2.5 millimetres, which is the figure for the limit between gravel and sand most in accord with the usage of practical engineers (see p. 38).[2] Hence for practical purposes a pebble deposit may be defined as one in which the majority of the com-ponents have a diameter between 10 centimetres and 2.5 millimetres. The presence of a certain amount of sand in addition does not vitiate this definition.)

Deposits of this class have a very wide distribu-tion in nature, and may be formed under a great variety of conditions. (In the sea they are almost confined to the shore and shallow-water zones, where however they are very abundant. They are also

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[1] Richthofen, *Führer für Forschungsreisende*, Berlin, 1886, p. 94 (from Latin, *squama*, a scale).

[2] For the mechanical analysis of soils, however, agriculturists have adopted a somewhat different standard.

largely prevalent as component parts of all facies of deposition of the continental type : in short, pebble deposits are specially characteristic of shallow-water and terrestrial conditions.

According to the source or sources from which they are derived, the pebbles may consist of fragments of any rock whatever, igneous or sedimentary. It is seldom that a gravel is composed entirely of fragments of one kind of rock (*monogenetic*) ; much more frequently it is *polygenetic*, or composed of many kinds. The nearest approach to a monogenetic composition in this country is found in some of the flint gravels of the south and south-east of England, where a considerable search is sometimes necessary before a pebble of any other kind can be found. Gravels of glacial origin, either direct or indirect, generally show the greatest variety of pebbles, since they often include material transported for very long distances and even across the sea ; as an example we may quote the large number of Scotch and Scandinavian pebbles in the glacial gravels of Norfolk, Cambridgeshire,[1] and Yorkshire. The gravels of sea - beaches also often show great variety, since the materials of which they are composed may have travelled for long distances ; but a river gravel, in a non-glaciated region, is necessarily composed only of material obtained from the area drained by the river. It must always be borne in mind, however, that in the alternating periods of

[1] Rastall and Romanes, " The Boulders of the Cambridge Drift," *Quart. Journ. Geol. Soc.*, vol. lxv, 1909, p. 246.

denudation and deposition that constitute the geo-
logical history of any given region the constituent
pebbles of gravels are often handed on from one deposit
to another with very little change, except possibly a
slight reduction in size, or a somewhat more rounded
outline.) It is often tacitly assumed that the materials
of every gravel-bed have been worked into their
present size and shape under existing conditions and
during what may for convenience be called the present
geological cycle ; but this is very far from being the
case. A great part of the material of existing beaches
is undoubtedly obtained at second-hand, and every
pebble may have had a long and varied geological
career since it was first separated from its parent rock.
A very good instance of this kind is afforded by the
beach at and near Budleigh Salterton, in Devonshire,
which is almost wholly formed of ovoid pebbles from
the Bunter pebble-bed, near the base of the Trias,
which here forms part of the cliffs. On the eastern
coast of England again, where glacial accumulations
are abundant, the pebbles in the beach gravels consist
very largely of far-travelled rocks, derived directly
from the boulder-clay and other glacial deposits ; and
among these are a considerable number of pebbles
from the Old Red conglomerates of Forfar and Kin-
cardine that have undergone scarcely any change in
size or shape. In fact, it is probable that pebbles of
certain particularly hard rocks have been transferred
from one conglomerate (or consolidated pebble-bed)
to another throughout the greater part of geological

history, or at any rate since the action of moving water and ice began to be important factors in earth-history.

The forms assumed by pebbles naturally vary according to their manner of origin, and in this respect the consideration just dealt with is of very great importance. If a pebble is thoroughly well-rounded at the time when it gets into a beach gravel, for example, it is likely to remain so, and to retain its original shape to a great extent, even if this differs somewhat from the shape proper to its new conditions. So, for example, the beach-pebbles at Budleigh Salterton, mentioned above, retain their original form, which is, in point of fact, more characteristic of river gravels than of sea-beaches, and it is believed that they were actually formed by rivers.[1] On the other hand, pebbles derived from the boulder-clay often show a markedly sub-angular form; that is, the general outline is angular, but the corners are rounded off : the amount of rounding depends on the length of time during which the pebble has been exposed to the action of moving water.

For the reasons above stated, it is difficult to lay down any precise rule as to the form of pebble characteristic of deposition under given conditions. It may, however, be stated in general terms that on sea-beaches and in river-beds the pebbles usually possess curved and smooth outlines ; they may be

[1] Bonney, "The Bunter Pebble-beds of the Midlands," *Quart. Journ. Geol. Soc.*, vol. lvi, 1900, p. 287 ; also *Geol. Mag.*, 1895, p. 75.

spherical or of a more or less flattened ovoid form ;
angular outlines indicate recent derivation from the
parent rock or from some pre-existing deposit. In
such aqueous deposits the surfaces of the pebbles
are usually smooth and free from pitting, unless the
constituents of the pebble vary much in hardness.
In glacial accumulations the constituent blocks
show much more variety of outline ; they are often
angular, with sharp outlines, and they frequently
possess facetted faces and scratches. Glacial stria-
tions, however, do not develop well on all rocks.
They are specially conspicuous on pebbles of lime-
stone and of serpentine, but are generally difficult to
detect on harder rocks. In fluvio-glacial gravels the
pebbles are generally much like those of ordinary
rivers, but some facetted or striated blocks are usually
present. The degree of rounding depends obviously
upon the amount of water-transport which the material
has undergone.

  Many of the pebbles found in deserts or in other
places where wind-action is dominant have a peculiar
triangular section, with two flat sides meeting in a
ridge, which is often quite sharp. This shape, which
is known as " Dreikanter," is due to the abrading
action of sand grains carried along by a wind blowing
prevalently in one direction. Owing also to the effect
of moving sand many desert pebbles have well-polished
surfaces, and large stones sometimes show under-
cutting when they have been isolated for any length
of time.

It is evidently impossible to give a complete account of all known varieties of pebble deposits, since their constituents vary widely. The pebbles may consist of fragments of any rocks whatever, according to the source from which they have been derived; and since the fragments are of considerable size, as a rule they are mineral aggregates rather than single minerals.

When a formation, consisting of hard masses embedded in a softer or more soluble matrix, undergoes denudation, the hard and heavy inclusions are left behind and form a residual deposit. Such has been the case in many places with the flints in the Chalk, which often form thick masses of flint-gravel capping the Chalk hills. Over a large extent of country the Chalk is covered by a deposit known as the Clay-with-Flints, which was formerly believed to consist entirely of the heavy and insoluble residue of the Chalk itself; but evidence has recently been brought forward to show that it is derived in part from Tertiary beds which once overlay the Chalk, and the residue of these beds is now mixed up with that from the Chalk (see p. 339). The Cannon-shot gravels and Plateau gravels of Norfolk and Cambridgeshire consist chiefly of flints, but contain also many far-travelled rocks, and they are undoubtedly the heavy residue of the boulder-clay, from which the finer portion has been removed by running water. The weathering of ancient conglomerates often gives rise to residual pebble deposits, as on the Witwatersrand and in parts of Cape Colony.

Gravels of purely marine origin are very abundant all along the south coast of England, and form, in particular, two well-known deposits—the Chesil Beach in Dorset and Dungeness in Kent. The great majority of the pebbles in these deposits are of flint, and they are for the most part extremely well-rounded. Since the material travels in the main from west to east (with some local exceptions), a certain number of pebbles derived from the hard rocks of Devon and Cornwall are present. The materials of the beach gravels of eastern England, of Wales, of Lancashire and Cumberland, and of Scotland are largely derived from glacial deposits, and their constituents are consequently of a very varied nature.[1]

Great masses of gravel form terraces at varying heights above the courses of the Thames and of most other rivers of southern England. These are chiefly composed of flints that have been weathered out from the Chalk during Tertiary times, and carried down to the river by running water and soil-creep.[2] In eastern England the materials of the gravel terraces are largely derived from glacial deposits, and include, therefore, many far-travelled pebbles in addition to flints. In the more hilly regions of Britain the

[1] For much information on the beaches of the British Isles, see *Third Report of the Royal Commission on Coast Erosion,* 1911.

[2] General accounts of the gravels of the Thames Valley will be found in several chapters of the Jubilee Volume of the Geologists' Association, 1910. See also Salter, " On the Superficial Deposits of Central and Parts of Southern England," *Proc. Geol. Assoc.,* vol. xix, 1905, p. 1.

terracing is less well-marked, and the constituents of the river gravels vary according to the district. Mammalian remains and flint implements are often abundant in river gravels.

Torrential gravels are abundant also in the valleys and on the flanks of the Alps. They are of enormous thickness, and have a very wide. extension over the low ground north of the Alps and Carpathians. From a very early period to the present time their formation has been more or less continuous. Of these the freshwater Molasse of Upper Tertiary age consists of sandstones and conglomerates formed by stream action ; the Nagelfluh is a conglomerate, partly of glacial origin and re-sorted by water ; while the recent Deckenschotter includes glacial deposits and the gravels of river terraces.[1]

In certain parts of the south of England which were not covered by an ice-sheet during the glacial period there are extensive deposits of a peculiar character, which are known as *Coombe Rock* or *Head*.[2] The Coombe Rock in its typical development is a rubbly mass of unrolled flints and fragments of Chalk, with some earthy interstitial matter, but in places it passes into loams and brick-earth. It occupies the bottoms of the dry valleys or coombes in the South

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[1] Penck and Brückner, *Die Alpen im Eiszeitalter*, Leipzig, 1909, pp. 109 and 395 ; Bonney, *The Building of the Alps*, London, 1912, p. 150. .

[2] Reid, *Quart. Journ. Geol. Soc.*, vol. xliii, 1887, p. 364. Prestwich, *ibid.*, vol. xlviii, 1892, p. 263. For a short general account of the Coombe Rock, see Elsden, *Geol. Assoc.*, Jubilee Volume, p. 275.

Downs, and spreads far over the coastal plain at their
foot. It is clearly not residual, but is believed to be
a torrential deposit formed during the glacial period
when the ground was permanently frozen to a con-
siderable depth, as in the tundras of Siberia and North
America. Under such conditions water would not
sink into the Chalk, but would flow over its surface,
and in so doing would give rise to active denudation.
The name " head " is applied to surface deposits in
Cornwall which carry tinstone and wolfram, and are
of similar origin (see p. 60).

Sand Deposits. Sand is specially characteristic
of shallow-water and land deposits, whether formed
by running water, wind, or ice. In accordance with
the definition given for gravel, the limit of size for
coarse sand must be taken at 2.5 mm., while the lower
limit for fine sand is conveniently fixed by the size at
which the individual grains are just visible to the
naked eye, viz., approximately 0.05 mm.[1] Material

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[1] The choice of suitable limits has not been easy on account
of the diversity of opinion that appears to exist as to what is
meant by " sand " and " gravel " respectively.

After consulting both geologists and practical engineers the
figures given have been adopted as being those most in accord
with current opinion. Among others Messrs. Sulman and Picard,
the well-known metallurgists, were consulted, and Mr. H. L.
Sulman, past-President of the Institution of Mining and Metal-
lurgy, was good enough to state his opinion in the following
terms :

" To the practical Metallurgist and the Mining Engineer the
term ' sand ' has a very definite signification. Engaged as he
constantly is in the crushing of mineral-bearing rock for the
purpose either of the proximate separation of the valuable mineral,
or the solution of gold, silver, copper, etc., therefrom—operations

between 0.05 mm. and 0.005 mm. is silt : below this limit the term " clay " is used.

The shape of sand-grains is closely connected with their mode of origin. The following generalisation, though not without exceptions, is true for the most part. (Sand formed in moving water, either in the sea or in rivers, has a subangular character, the general form of the constituent grains being much the same as that of the subangular pebbles before described; wind-blown sands are characterised by remarkably well-rounded grains (millet-seed sands); while the component grains of glacial sands are very angular, when they have not been subsequently modified by water. These differences are easily accounted for. In running water there is both rolling and sliding, but the latter is dominant; wind-blown material undergoes a large amount of rolling, whereas the movement of ice is almost all sliding; hence the differences of form are easily explained. In some sands formed by water-action the majority of the grains are very angular.

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which involve the pulverising of many million tons of material annually,—his employment of the word to describe a certain range of comminuted products constitutes a definition of considerable technical importance. The following particle-sizes are those to which he ascribes definite names :

Particles passing through square aperture of a width	Name.
Varying between 2.5 and 0.75 mm. . .	' Coarse sand.'
,, ,, 0.75 , 0.10 ,, . .	' Sand.'
,, ,, 0.10 ,, 0.05 ,, . .	' Fine sand.' "

See also Boswell, *A Memoir of British Resources of Sands and Rocks used in Glass-making*, London, 1918, and *A Memoir on British Resources of Refractory Sands*, Part I., London, 1918.

This is due to the rapid accumulation of material which has not travelled far enough to have the sharp corners rubbed off, each layer having been so quickly buried under succeeding layers that little or no movement was possible after deposition. Sometimes, on the other hand, aqueous sands have a well-rounded character, which is possibly the result of incessant to-and-fro, or circular, movement in eddies, or in pot-holes.

The constituent grains of a sand may consist of any kind of rock, but individual minerals are more common. The number of different minerals that have been found as components of sands is very great, and includes almost all the constituents of the igneous, sedimentary, and metamorphic rocks. But since the softer minerals tend to be destroyed by abrasion, there is a predominance of the harder varieties. The commonest and most characteristic of all the minerals found in sands is quartz, since it is not only hard and stable, but very abundant in many rocks. Many sands consist almost exclusively of grains of quartz. Muscovite is also abundant and very stable, and tends to accumulate in layers. Sorby[1] has shown that under identical conditions particles of quartz and muscovite settle in water at very different rates, the quartz coming down before the muscovite. This is accounted for by the greater surface area of the muscovite flakes as

[1] Sorby, " On the Application of Quantitative Methods to the Study of the Structure and History of Rocks," *Quart. Journ. Geol. Soc.*, vol. lxiv, 1908, p. 171.

compared with rounded grains of quartz of the same
weight. Biotite is rare in sediments, owing to its being
more readily decomposed than muscovite. Felspar is
common, but since it is easily attacked by carbonated
water, fresh felspar is more characteristic of æolian and
other terrestrial deposits than of those laid down in
water. Hornblende, augite, and hypersthene some-
times occur in deposits derived from areas where

Fig. 1.—Rutile, Knee-
shaped Twin.

From the Bunter Pebble-
bed. × 150. (After H. H.
Thomas.)
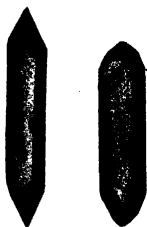
Fig. 2.—Zircon Crystals.

From the Bunter Pebble-
bed. × 150. (After H. H.
Thomas.)

igneous rocks are undergoing denudation. Of the
other normal constituents of igneous rocks, magnetite
and ilmenite often accumulate in considerable amount
and are then known as *black sands* (see p. 61). Zircon
and rutile are found in almost all sands. They are
minerals of extraordinary stability, and appear to
be almost indestructible, being handed on from one
sedimentary deposit to another with little or no change.
Brookite and anatase are somewhat more local. The

hard and stable minerals of contact metamorphism and
of pneumatolysis, such as tourmaline, kyanite, stauro-
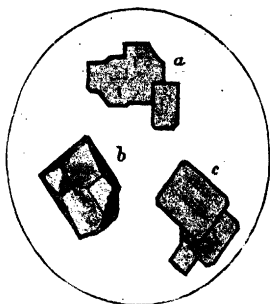
FIG. 3.—ANATASE CRYSTALS.

a. From the Bunter Pebble-bed of Newton Poppleford, Devon.
    × 115. b. From Lower Breccias of the Ness, Teignmouth.
    × 100. c. From Lower Sandstones of Honiton Clyst, Devon.
    × 200. (After H. H. Thomas.)

FIG. 4.—TOURMALINE CRYSTALS.

From the Bunter Pebble-bed. × 150. (After H. H. Thomas.)

lite, garnet, sillimanite, etc., are very common;
andalusite and cordierite, however, being less stable,

are more infrequent; they are known, however, in some Tertiary and Recent sands.[1] Other minerals sometimes observed are apatite, sphene, corundum, and fluorspar.

In Tertiary and Recent sands flint is a very common constituent, occurring sometimes in rounded grains,
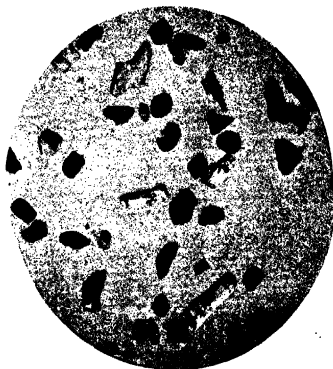
FIG. 5.—KYANITE CRYSTALS (LIGHT-COLOURED).

In Sandringham Sands. From Castle Rising, Norfolk. × 22.

but more commonly as minute angular chips. Many other fragments of fine-grained rocks, such as chert,

[1] Thomas, " Detrital Andalusite in Tertiary and Post-Tertiary Sands," *Min. Mag.*, vol. xv, 1909, p. 241. Davies (*Quart. Journ. Geol. Soc.*, vol. lxviii, 1912, p. 249), however, mentions having found perfectly fresh and pleochroic andalusite in the Bagshot Sands of Brentwood, the Woolwich and Reading Beds of Plumstead and Northwood, the Thanet Sand of Crayford, the Folkestone Sands (Lower Greensand) of Dunton Green, Limpsfield and Reigate, and the Wealden Ironsands of Shotover Hill.

jasper, hornstone, chalcedony, hälleflinta, and fine-grained volcanic ash, occur in sands of all ages. In regions of crystalline schists, small fragments of mica-schist, quartzite, and granulite are often recognisable. Minerals of economic importance occurring in sands are described elsewhere (see p. 56 *et seq.*).

Sands formed in the sea nearly always contain a
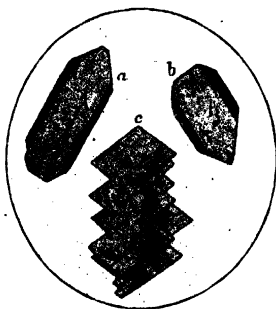
FIG. 6.—STAUROLITE CRYSTALS.

a. Perfect crystal (010, 110, 101, 001). From Blown Sand of Newgale, Pembrokeshire. *b.* Perfect crystal. From the Pliocene of Lenham, Kent. *c.* A cleaved fragment. From the Bunter Pebble-bed of Budleigh Salterton, Devon. (After H. H. Thomas.)

certain amount of material of organic origin, such as fragments of shells and coral; when these are very abundant the terms shell-sand and coral-sand are used to describe the deposits (see p. 129). The occurrence of glauconite in large quantities as a con-stituent of marine sands is interesting. Glauconite is a silicate of potash and alumina with some iron, and

it is likely that it owes its origin to the decomposition of potash-felspar and potash-mica in igneous and metamorphic rocks. This mineral has been repeatedly analysed, but unfortunately with conflicting results, so that it is impossible to assign a chemical formula to the mineral, or to state the reaction or series of reactions by which it is formed. It is most commonly found, in modern deposits, in moderately deep water, where the submarine slopes are fairly steep, and the adjoining coast consists of crystalline rocks. But in some deposits, such as the Greensands of the Cretaceous, glauconite must have been formed in shallow water, in which strong currents prevailed. The mineral is nearly always associated with phosphatic nodules. In many cases it is found filling the body-cavities of Foraminifera and other organisms, but it also occurs as incrustations on quartz grains and other inorganic substances. Murray and Philippi [1] suggest that glauconite is of bacterial origin, and that its restriction to marine deposits is to be attributed to the absence of the necessary bacteria in fresh water. Isolated grains of glauconite are common in modern sediments formed near continental land, especially in regions where warm and cold currents meet; the best-known examples are the green sands and green muds of the Agulhas Bank, off the southern extremity of Africa. According to Murray and Hjort,[2] glauconite is a mineral belonging

[1] *Wiss. Ergebn. d. deuts. Tief-See Expedition*, x.
[2] Murray and Hjort, *The Depths of the Ocean* London, 1912, p. 189.

essentially to the reducing areas of the ocean. Glauconite is common among rather coarse-textured sediments of all ages, even as far back as the Cambrian ; it is very abundant, for instance, in the Wrekin quartzite and Comley beds in Shropshire. In Jurassic rocks it frequently accompanies small local unconformities and " wash-outs," but its most typical development is in the Cretaceous, both in the Lower Greensand and in the sandy facies of the Gault (the so-called Upper Greensand). It is noticeable that in the north-east of Ireland the sandy glauconitic facies extends up to a much higher horizon than in England, and includes the representatives of the Lower and Middle Chalk, which are lithologically greensands, although they contain the zone - fossils of the Cenomanian and Turonian.

Sands of exceptional composition are met with on the beaches surrounding many of the volcanic islands of the Pacific. For instance, a sand found on the coast of Oahu, in the Hawaiian Islands, consists almost entirely of olivine and magnetite, the larger grains being rounded, but the smaller often presenting sharp crystal outlines. This sand is derived from the disintegration of a fresh basaltic lava. Much commoner, however, are beach deposits, consisting partly of calcareous matter of organic origin, partly of volcanic material, often chiefly fragments of glass, or of the decomposition - product of volcanic glass, known as palagonite. These deposits grade, on the one hand, into coral sands, and, on the other, into

tuffs, according to the proportions in which the con-
stituents are present. Well-known examples are those
of the Tonga Islands and other groups in the central
Pacific.[1] Pure coral sands are referred to elsewhere
under the heading of Organic Deposits. (See p. 128.)

Sands are formed under very varied conditions,
which, for convenience, may be divided into four
principal groups, namely, *marine, fresh-water, glacial,*
and *terrestrial.*

Sea - sand forms the lower portion of a normal
beach, and a similar deposit extends far below low-
water mark, usually covering the submerged con-
tinental shelf down to a depth of nearly 100 fathoms.
The chief exception to this is off the mouths of large
rivers, or in some partially enclosed seas, where mud
is dominant. Under ordinary conditions the further
the material is from the land the finer its grain ;
eventually it grades into mud. Since sea-sand under-
goes considerable movement on beaches, the amount
present at any given time depends to a large extent on
the weather of the previous period. Broadly speaking,
sand disappears during storms and accumulates in fair
weather. On shores exposed to a prevailing wind
much sand is carried inland to form sand-dunes, as on
the coasts of Wales, Lancashire, and Cumberland.
Modern sea-sands usually contain abundant shells and

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[1] Lister, "Notes on the Geology of the Tonga Islands,"
Quart. Journ. Geol. Soc., vol. xlvii, 1891, p. 590. Guppy, *The
Solomon Islands, their Geology,* etc., London, 1887, chap. v.

other organic remains, and taking this fact into con-
sideration, it is curious that the older rocks formed
from sea-sands are so often wholly unfossiliferous ; the
explanation is probably that the calcareous shells are
dissolved during the processes of cementation and
metasomatism.   The number of minerals recognisable
in sea-sands is very large ; but little work has been done
toward the systematic investigation of modern marine
sands in comparison with the attention paid to older
sediments and to modern sands of terrestrial origin.

A detailed examination of the heavy minerals of the
Lower Greensand along the stretch of country between
Bedfordshire and the Wash has shown that the
following minerals are of universal occurrence : zircon,
kyanite, staurolite, tourmaline, and rutile ; otherwise
local differences can be established.   In Norfolk
garnet and blue soda-hornblende are frequent, ex-
tending as far south as Ely.   The last named is almost
certainly Scandinavian.   Green mica is also only seen ·
near Sandringham.   Farther west are found colour-
less pyroxene and green epidote, with abundant blue
tourmaline, and locally a considerable amount of
sphene.   In the extreme west of the area examined a
few grains were believed to be cassiterite, indicating
derivation from the south-west.[1]

Dick,[2] who carefully examined the mineral com-

[1] Rastall, *Geol. Mag.*, vol. lvi, 1919, p. 211.
[2] Dick, " On Zircons and other Minerals contained in Sands,"
Nature, vol. xxxvi, p. 91.   Bréon, " Séparation des Minéraux
microscopiques lourds," *Bull. Soc. Min. France*, No. 3, 1880,
p. 46.

position of the marine Tertiary Bagshot sands, found the grains remarkably small, with an average diameter of about .125 mm. Heavy minerals, he found, are unusually abundant, amounting in some samples to as much as 4 per cent. He estimated the mineralogical composition of these sands to be as follows :

Quartz.	.	.	.	.	75	per cent.
Felspar	.	.	.	.	20	,,
Iron ores	.	.	.	.	2	,,
Clay .	.	.	.	.	1	,,
Zircon .	.	.	.	.	0.5	,,
Rutile .	.	.	.	.	0.2	,,
Tourmaline .	.	.	.	.	.1	,,
Various	.	.	.	.	1.2	,,

The last item includes some kyanite and some glauconite. The crystals of zircon, rutile, and tourmaline are sometimes worn and rounded ; sometimes they present good crystal faces. A little flint is also present, as is to be expected in a Tertiary deposit.

The marine sands of Île de Groix and other places in Brittany show a much greater variety. Among the minerals identified in sands from these localities are iron ores (magnetite, hæmatite, ilmenite), garnet, staurolite, hornblende, glaucophane, andalusite, sphene, augite, cassiterite, and white mica, together with quartz and felspar.

Little attention seems to have been paid to the composition and characters of modern river-sands, except in instances where minerals of economic value are present, and even of these the majority must be

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regarded as fine gravels rather than sands as defined in this chapter. Some interesting work has, however, been done by H. H. Thomas [1] on an ancient fluviatile sand, namely, that of the New Red Sandstone of the west of England. His researches led him to the conclusion that the source of much of the material is in a region of ancient crystalline and metamorphic rocks situated to the south and west of the area now occupied by the sandy strata in question. The total number of minerals identified is large, but the following list includes the more characteristic species : garnet, magnetite, anatase, rutile, zircon, ilmenite, tourmaline, brookite, staurolite, chlorite, muscovite, orthoclase, microcline, plagioclase, and leucoxene. In certain beds the mineral grains are angular ; but more usually they are distinctly rounded, and some samples resemble the millet-seed sands of modern deserts. The cement is usually both ferruginous and calcareous, while barytes and gypsum are locally abundant.

Sands of fresh-water origin are found forming the beaches of the larger fresh-water lakes, although there is a strong tendency for the shore to be bordered by a fringe of vegetation, especially if it is at all sheltered from the winds : it is chiefly in exposed places that purely fragmental beach deposits accumulate. These lake-sands do not differ in any important respect from

[1] Thomas, " Minerals of the Bunter Pebble-bed," *Quart. Journ. Geol. Soc.*, vol. lviii, 1902, pp. 620-31 ; and " A Contribution to the Petrography of the New Red Sandstone of the West of England," *ibid.*, vol. lxv, 1909, pp. 229-45.

those of the sea.[1] River-sands again are abundant, and tend to accumulate where the current is weak. They are often deposited over considerable areas during floods.[2] Sands of estuarine origin are common, and show a close resemblance to sea-sands, except that their organic contents are often a mixture of terrestrial and marine forms. Plant-remains are specially abundant, as in the Jurassic estuarine series of the Yorkshire coast. In these sands there is often a rapid alternation of sandy and muddy sediments, owing to the flow of the river being subject to periodical variation.

Terrestrial sand deposits are as a rule almost wholly due to wind-action. Sand-dunes [3] are formed along many of the coast-lines of temperate regions, as in Cumberland, Lancashire, Wales, Cornwall, Holland, the Landes of south-western France, the Moray Firth, South-West Africa, and numerous other localities. In nearly all cases the coasts bordered by sand-dunes are exposed to a fairly large expanse of sea, with prevalent on-shore winds. The sand is formed in the first place by the sea, and carried inland by the winds. Consequently the sand-grains are often angular or sub-angular, and rarely show the high degree of rounding characteristic of desert sands. It follows also that the constituent materials are in most cases the same as

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[1] Hutchings, " Notes on Sediments dredged from the English Lakes," *Geol. Mag.,* 1894, p. 300.

[2] Relf, *Geol. Mag.,* 1916, p. 295.

[3] Vaughan Cornish, " On the Formation of Sand-dunes," *Geogr. Journ.,* vol. ix, 1897, p. 278.

those of the adjacent beach-sands, though a certain
amount of gravitational sorting has usually taken place.
The dune-sands of Holland have been exhaustively
investigated by Retgers.[1] This author found that in
size of grain dune-sand is much more uniform than sea-
sand, and he considers the magnitude to be a function
of the wind-pressure ; in the case in question the
normal diameter of the grains is about .2 mm. The
predominant mineral he found to be quartz, con-
stituting about 85 per cent. of the whole. Of the rest
the most abundant are garnet, augite, staurolite,
magnetite, zircon, rutile, tourmaline, epidote ; while
orthoclase, hornblende, ilmenite, apatite, and calcite
are present in less quantity. Much more rare are
plagioclase, microcline, cordierite, sphene, sillimanite,
olivine, kyanite, corundum, and spinel. It is note-
worthy that no mica was observed in any sample.

   The most characteristic of all terrestrial sand de-
posits are those formed in true desert regions ; for
here the action of running water is entirely excluded,
except under very special circumstances. The dis-
integration of the rock is effected by the so-called *dry
weathering*, and the only agent of transport is the
wind. A noteworthy feature is the conspicuous
rounding of the grains, producing what is known as
the *millet-seed* character. There are two reasons for
the greater rounding of desert sands, as compared with

   [1] Retgers, " Über die mineralogische und chemische Zusam-
mensetzung der Dünensande Hollands . . .," *Neues Jahrbuch
für Mineralogie*, 1895, p. 22. Abstract in *Min. Mag.*, vol. xi,
1897, p. 113.

sands laid down in water : firstly, under wind-action the rolling motion is predominant, while sliding is subordinate ; secondly, since the sand-grains move in air, their whole weight is effective in producing friction, whereas in water only a part comes into play.

The composition of desert sands depends on that of the rocks from which they are derived. These, however, need not necessarily be near at hand, since wind can transport material immense distances, even uphill and across open water. As a rule, material of organic origin is completely absent ; occasionally, however, where advancing sands have overwhelmed a hitherto fertile region, as in parts of the Nile valley, fragments of wood and other vegetable or animal matter may be present.

The mineralogical composition of a sand from the Algerian Sahara was investigated by Thoulet [1] ; it was of a reddish yellow or ochreous colour, and consisted of much-rounded grains. The majority of the grains were quartz, but a fair amount of felspar was present, and some rather large grains of iron-ore. The amount of heavy residue with a density greater than 2.8 was small, amounting only to about 0.25 per cent. The constituents recorded were magnetite, ilmenite or chromite, pyroxene, amphibole, pink garnets and olivine, but no mica was observed.

The absence of mica in wind-blown sands is evidently a characteristic feature—all the more notice-

[1] Thoulet, " Étude minéralogique d'un sable du Sahara," *Bull. Soc. Min. France*, 4, 1881, p. 262.

able from the great abundance of this mineral in sands
laid down in water. This phenomenon is evidently
connected with the perfection of the cleavage of the
mineral, which enables it to split into thin flakes under
impact and to be blown by the wind. It has often
been stated that cleavable and unstable minerals do
not occur in wind-blown sands, but Retgers has shown
that this is not correct, calcite, cordierite, olivine,
etc., having been found by him in the dune-sands of
Scheveningen.

On the subject of the constitution and characters
of *glacial sands* little information is available; it is
usually a matter of much uncertainty whether a deposit
described as a glacial sand has really been formed by
ice alone, or whether it has been subsequently worked
up and re-deposited by running water. It seems
probable, indeed, that all the so-called glacial sands
really belong to the fluvio-glacial group, and that
water has always played some part in their transport
and accumulation. Since, however, they have usually
not been transported far by water, their grains tend to
preserve a sharply angular form, and there is less
classification by size in glacial deposits than in those
formed wholly by moving water. Sometimes, how-
ever, as in Lancashire and Cumberland, glacial
deposits contain many well-rounded grains that have
been derived from the Trias and older formations,
mixed with sharply angular chips of quartz and other
minerals.

Since little has been published on this subject, a

specimen of glacial sand was specially examined for this work. It was obtained from a locality near Whitby in Yorkshire, about two miles from the coast, where it forms a lenticular patch between two masses of boulder-clay and is undoubtedly of glacial origin. It contains many small chips of a dark grey shaly rock, evidently derived from the Lias, the chief rock of the district. (The grains of quartz and other minerals are notably angular, and heavy minerals of a density greater than 2.8 are present in large quantity. The most abundant and characteristic of these is pink garnet, and other minerals identified are tourmaline, green hornblende, pale augite, hypersthene, zircon, rutile, kyanite, staurolite, and andalusite in small quantity. Iron-ores are abundant.[1]

The mineral composition of the late Pleistocene marsh-deposit known as the Arctic Bed, occurring in the valley of the river Lea, has recently been made the subject of study by Mr. G. M. Davies.[2] The material examined consisted of a grey sandy loam containing a varying amount of vegetable matter and a few ostracods, foraminifera, and broken gastropod shells. Quartz was the dominant constituent of the sandy residue; flint and quartzite were common constituents; felspar and glauconite less so. The heavy residue obtained on treatment with bromoform consisted largely of plant remains coated with pyrites,

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[1] For a description of a glacial sand from the Tirol, see Wichmann, *Tschermak's Min. Pet. Mitth.*, vol. vii, 1886, p. 452.

[2] *Quart. Journ. Geol. Soc.*, vol. lxviii, 1912, p. 243.

and to a less extent with pyrrhotite and iron oxide.
Limonite was present as a product of the oxidation of
the sulphides. When freed from the sulphides and
oxide of iron, the heavy detrital minerals were found to
be garnet, tourmaline, staurolite, hornblende, epidote,
zircon, kyanite, ilmenite, rutile, andalusite, apatite,
mica, and a monoclinic pyroxene, the order given being
that of relative abundance.

Gold Placers.—Of importance from the economic
point of view are the auriferous gravel and sand
deposits (placers) that have been worked for gold
throughout the world since the earliest times. The
gold in these gravels is in the main derived from the
denudation of formations containing auriferous quartz
veins.

There are two main types of these deposits, namely,
(1) *Residual* or *eluvial gold gravels* (*Bergseifen*), which
are formed by the disintegration *in situ* of the vein
outcrop [1] or by a concentration of the heavier metallic
constituents of the shoad material on the hillside
immediately below the outcrop. These are of no
great economic importance, and are mainly confined
to tropical countries : they are akin to the shallow
surface-accumulations that occur in desert countries,
where the concentration of the gold-bearing particles
has been aided by wind-action (*e.g.* in the so-called
" cement " deposits of Coolgardie in West Australia [2]).

[1] For this Becker (*Min. Sci. Press*, March 28, 1908, p. 289)
proposes the term " saprolite."
[2] Rickard, *Trans. Amer. Inst. Mining Eng.*, vol. xxviii, 1898,
p. 490.

(2) *Alluvial gravels* (true placer deposits), accumulating in the valleys of rivers and in lakes, to which they have been transported by running water. These are of great economic importance, and have in the past yielded the bulk of the world's output of gold. The gold is concentrated in the coarse gravels and among the boulders at the bottom of the placers, the most valuable accumulations being often actually on the bed-rock itself. If the latter happens to consist of steeply dipping schists or slates, the upturned edges of the latter act as natural riffles or bars to catch and retain the gold particles. Accumulation also takes place on what are known as " false bottoms," which are beds of clay or sand cemented by iron (" pan "), alternating with the beds of gravel.

Placer gold is usually associated with a heavy black sand consisting of magnetite, ilmenite, and hæmatite, together with chromite, garnet, zircon, spinel, and other heavy resistant minerals ; but obviously the particular association is determined by the nature of the parent rock.[1] The character of the gold is very variable : it occurs in flat scales and flakes, in rounded particles, and as irregularly-shaped grains and nuggets bearing evidence of much attrition. Crystallised gold also occurs. Placer gold varies in size from the finest dust to nuggets weighing thousands of ounces. With regard to the large nuggets it is a moot point whether these owe their origin entirely to mechanical deposition or whether they have grown by chemical accretion

[1] Shannon, *Proc. U.S. Nat. Mus.*, vol. lx, 1921, pp. 1-33.

since the deposition of the gravel deposit. Although there is much to be said on both sides, the fact that auriferous pyrites is found replacing the woody fibre of tree stems in the alluvial drifts of Victoria and California clearly shows that under favourable conditions an enrichment through chemical action (that is, solution and recrystallisation) can take place.

Some of the richest gravels are formed by a secondary mechanical concentration or re-sorting of earlier auriferous gravels, which to-day are found as terraces several hundred feet above the present river-beds.

Placer deposits occur in the river systems of every part of the world ; but the greatest amount of gold has been won from the Recent and Pleistocene gravels of California, Alaska, Australia, and Siberia. The older gravels are often deeply buried under a thick cover (" over-burden ") of clay, soil, peat, and moss, which is sometimes permanently frozen, as in the tundras of Siberia [1] and Alaska. In California and Australia the gravels of the ancient river systems are also often concealed beneath later flows of lava, and are then known as " deep leads."

Of a somewhat different character are the auriferous beach deposits or marine placers which are formed on certain coasts where the conditions are favourable for the separation, by surf action, of the gold and heavy

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[1] In the Nerchinsk district the permanent frost extends downward through the over-burden and gravel into the solid rock, in which cracks are sometimes filled with ice to a depth of 100 feet. Purington, *Mining Mag.*, 1912, p. 50.

minerals from the sand and lighter stones. Such deposits occur in New Zealand, on the beaches of Oregon, Alaska (Nome and Cape Yagtag), Chile, and Nova Scotia. Usually the gold occurs in a black sand consisting of magnetite and hæmatite, but these mineral associations are not constant ; in the Cape Yagtag deposit, for instance, the iron-ores are absent, their places being taken by garnet.

Platinum Placers.—The platiniferous placers of the River Iss and other rivers draining the eastern slopes of the Ural Mountains in the district of Nischne Tagilsk and Mount Solovief deserve special mention. In these deposits the platinum is associated with chromite and magnetite ; and their origin has been traced to intrusive masses of peridotite in which there has probably been a magmatic concentration of these minerals. Platinum is also occasionally associated with gold in the residual and alluvial gravels of California, British Columbia, Brazil, Colombia, and Borneo.

Stanniferous Gravel and Sand.—In districts where granite prevails the residual and river gravels often contain cassiterite, and such stanniferous gravels form the source of the bulk of the tin production of the world. In common association with the cassiterite are the minerals tourmaline, topaz, axinite, garnet, wolfram, scheelite, limonite, magnetite, and other heavy and indestructible minerals. As in the case of the gold-placers, the concentrates accumulate at the base of the gravel deposit on the bed-rock or floor on which they rest. The gravel itself consists

largely of tourmaliniferous quartz, greisen, and "capel" derived from the tin-bearing vein-material of the granitic rock, which by its denudation has given rise to the gravel deposits. Such stanniferous gravels occur in Cornwall, the Malay States, Australia, Tasmania, Bolivia, and in South Africa (Swaziland and the Transvaal).

Other Metalliferous Gravels and Sands.—A residual gravel (locally termed "head") with tin and wolfram occurs on Bodmin Moor in Cornwall. It consists of unrounded fragments of granite and vein quartz, through which the wolfram is disseminated in fairly large pieces. These deposits are of pre-glacial age, and appear to have escaped denudation by being frozen or covered with snow during a long period of their history.[1]

Similar residual gravels of pre-glacial age containing galena occur along the apex of veins of that mineral in North Wales, where they are sometimes 200 feet thick and have been profitably worked.[2] In Galicia gravels containing zinc ores, derived from veins in the Triassic limestone, have been exploited as a source of zinc.[3]

Chromite gravels are formed by the disintegration of chromite-bearing serpentine, as in New Caledonia; and there are numerous examples of similar deposits

[1] Barrow, "The High-level Platforms of Bodmin Moor, and their Relation to the Deposits of Stream Tin and Wolfram," *Quart. Journ. Geol. Soc.*, vol. lxiv, 1908, p. 384.

[2] Strahan, *Quart. Journ. Geol. Soc.*, vol. lxiv, 1908, p. 399.

[3] Bartonec, *Verh. k. k. geol. Reichsanst.*, 1889, p. 143. ·

ot iron ores (hæmatite, magnetite, and ilmenite, as *e.g.* those of Elba and New Zealand) and of manganese ores, that have weathered out and undergone selective accumulation not far from the original deposits that contained them.

Black Sands.—In many parts of the world, in the beds of rivers and more extensively on sea-beaches, there are found natural concentrations of the heavy minerals of sands. Around the shores of the Pacific large deposits of " black sand " are of some commercial importance. They consist chiefly of magnetite and ilmenite, and other heavy and stable minerals, but they are chiefly notable for containing workable quantities of gold, with sometimes platinum and diamonds. They are extensively developed in Alaska, Oregon and California, and in New Zealand : in all these localities they have yielded much gold, and some of the black sands of New Zealand are so rich in iron ores that it has been seriously proposed to smelt them for iron. Although known at various points round the Atlantic they are much less common. Black sands are always regarded as indicators of possible gold-values.

Gem-gravels.— Of economic importance also are the gem-gravels and sands in which, among other gems, diamond is found. These interesting accumulations owe their origin to a concentration of the same nature as that which produces the auriferous gravels— the difference in the material accumulated being solely dependent on the local occurrence of a parent rock containing the minerals characteristic of the deposits.

Diamantiferous gravels in which the diamonds are sufficiently numerous for profitable extraction are not common. That of the Vaal River is perhaps the best known. The so-called " river stones " occur over a large area in the Southern Transvaal, the Orange Free State, and Griqualand, from near Klerksdorp to Prieska —an area some 300 miles long by 50 miles wide. The solid rock underlying the whole of this area consists of amygdaloidal lavas belonging to the Ventersdorp system, with a thin cover of Dwyka conglomerate ; and the diamonds are found in residual and alluvial gravels derived from the Dwyka. The presence of the diamonds in this conglomerate has been ascribed to the " plucking " action of the ice-sheet in its passage over the Ventersdorp lavas in which they are supposed to have originated. The pebbles of the gravels consist mainly of amygdaloidal lava and of agate, chalcedony, jasper, and quartz, derived from the filling of cavities in the lavas. The diamonds are of all sizes ; and some show abrasion due to transportation, while others are sharp-edged. They are associated with a " deposit " of ilmenite, garnet, zircon, mica, and a banded spessartite-andalusite rock (the so-called " bantam ").

A secondary concentration of the residual gravels has taken place in the valleys of the Vaal River and its tributaries. These alluvial stones are mainly rounded—the few sharply-bounded crystals being probably derived directly from a kimberlite pipe ; but there is reason to believe that the bulk of the diamonds found within the Vaal River area have been

derived, in the first place, from the amygdaloidal lavas of the Ventersdorp system, and not from kimberlite diamond pipes, which are geologically of much more recent age.[1]

Diamonds have also been found in the surface deposits of the southern portion of South-West Africa. The exact nature of this occurrence is not clear, but it has been suggested that the stones were brought down from the Vaal River district by the Orange River, and distributed along the coast by ocean currents. Further concentration may have been effected by wind-action, since the diamonds are found in association with sand-dunes.

An occurrence of diamantiferous gravel at Soma-bula, in Rhodesia, contains the precious stones in a deposit of agate, jasper, quartz, quartzite, granite, and schist in association with garnet, zircon, beryl, corun-dum, kyanite, chrysoberyl, staurolite, rutile, tour-maline, muscovite, hæmatite, and magnetite. The diamantiferous concentrate is found in crevices of the uneven floor of the granite bed-rock, or between large boulders,[2] but it is not clear from the published descriptions whether the deposit is an ancient alluvial or a residual gravel.[3]

Interesting diamantiferous alluvial gravels occur in

[1] Voit, *Transactions Geol. Soc. South Africa*, vol. x, 1907, p. 101 ; Merensky, *ibid.*, p. 107 ; Harger, *ibid.*, vol. xii, 1910, p. 139.

[2] Mennell, *Geol. Mag.*, 1906, p. 460, and *Transactions Geol. Soc. South Africa*, 1908, p. 43.

[3] Flett, *Geol. Mag.*, 1906, p. 569.

Liberia, in the bed of the River Jiblong. Here the
diamond is associated with the following minerals :
kyanite, corundum, zircon, diopside, rutile, chromite,
magnetite, ilmenite, hæmatite, limonite, pyrites, and
gold, these minerals being derived by river erosion
from the lateritic weathering-products of an ancient
metamorphic series.[1]

The occurrence of diamonds in the alluvial gravels
of Borneo has long been known, and in places they
have been successfully worked. The associated
minerals are corundum, pyrites, gold, and platinum,
contained in a deposit ranging from a pebbly gravel
to the finest sand. The pebbles are chiefly quartz,
but metamorphic and igneous rocks also occur.[2]

The gem-gravels of Ceylon are characterised by
the presence of a considerable number of minerals
containing the rare earths. The residues, obtained
by treatment with heavy solutions, consist largely
of zircon, in association with tourmaline, spinel,
corundum, garnet, ilmenite, rutile, and chrysoberyl
(the alexandrite variety). Cassiterite and gold occur
sparingly. Among rare minerals found in these gravels
are geikielite ($MgO . TiO_2$), picroilmenite, thorianite,
thorite ($ThO_2 . SiO_2$), monazite ($(Ce,La,Di)PO_4$, fer-
gusonite ($(Y,Er,Ce) (Nb,Ta)O_4$, and baddeleyite (ZrO_2).[3]

Of late years monazite sands have become of great

[1] Hatch, "A Diamantiferous Gem-gravel from the West
Coast of Africa," *Geol. Mag.*, 1912, p. 106.

[2] Posewitz, *Borneo : Its Origin and Mineral Resources* (trans-
lated from the German by F. H. Hatch), London, 1892, p. 385.

[3] *Ceylon Administration Reports*, 1903-9.

economic importance, since this mineral is now the chief commercial source of the rare earths, especially thoria, the essential constituent of incandescent gas mantles. Monazite is a widely - spread accessory constituent of granitic rocks, and in certain localities, especially Brazil and southern India, it has accumulated in large quantities in the sands of the sea-coast, having been naturally concentrated by wave-action, along with garnet, zircon, ilmenite, magnetite, and other heavy and resistant minerals.

Dust and Mud Deposits.—The terms *dust* and *mud* are here employed for fragmental deposits of whatever origin, in which the particles have an average diameter of less than 0.05 mm. These are called dust when dry, and mud when wet. The deposits of this group differ from those hitherto described in the fact that they are plastic when partially wet, and possess the property of becoming coherent through drying alone, without the addition of any cementing material. There is therefore in this group an intermediate stage, namely that of the *clays*, between the incoherent and the completely cemented deposits (see p. 200).

In general terms it may be said that dusts are formed on land and muds in water. The dusts therefore are chiefly æolian deposits, the most characteristic being those of volcanic origin ; but others are known, as, for instance, the *loess*, which covers so much ground in central and eastern Europe and in Asia.[1]

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[1] See Richthofen, *China, Ergebnisse eigener Reisen und darauf gegründeter Studien*, Berlin, 1877.

The loess of China and of Europe is a fine calcareous silt or clay which is entirely unstratified, and very uniform in texture. It is quite soft, and crumbles between the fingers. It resists denudation, however, in an extraordinary manner, probably on account of its homogeneity, and often stands up as vertical walls hundreds of feet high. This property is probably assisted by the presence of numerous fine tubes arranged vertically and lined with calcium carbonate; they are supposed to have been formed in the first place by fibrous rootlets. Richthofen regards loess as fine detritus transported by wind into enclosed basins where it is deposited among growing vegetation. Loess is often very fertile and, when mixed with peaty matter, forms part of the famous Tchernozom or black earth of Russia—a deep black soil of extraordinary fertility.[1]

The loess of central Europe includes deposits of two different ages. According to Penck the older loess was formed in the period of warm and dry climate between the third and fourth glacial episodes, while the younger loess is post-glacial. Both are for the most part æolian deposits, formed by redistribution of fine glacial mud originally laid down in water, and after drying, carried by the wind often to considerable heights. A part, however, of the so-called loess of northern France, e.g. the Somme valley, and of Belgium, is precisely similar in character to the brick-earths of south-eastern

[1] For a description of the Tchernozom see p. 351.

England : the exact origin of these deposits is some-
what uncertain, but they are probably essentially
rain-wash.

Adobe is a deposit similar to loess and largely
developed in the Mississippi valley and elsewhere in
the United States ; but it is very doubtful whether
it was formed in the same way.

It is probable that the well-known Trias marls of
the British Isles owe their origin to a combination
of wind-transport and of deposition in water. Their
frequent interstratification with rock-salt and gypsum
indicates formation in salt lakes ; and there are other
facts that point to the existence of desert conditions.
It is most probable that the marls were formed by
the accumulation in salt lakes of fine dust carried
by the wind from the surrounding arid tracts. Sand-
storms and dust-storms are common and well-known
features of modern deserts, and by them vast quanti-
ties of fine sand and dust are transported for long
distances, and even across the sea, as described by
Darwin [1] in the case of some of the islands in the
Atlantic.

By the term *mud* are indicated the fine-textured
deposits formed in water. They are especially char-
acteristic of fairly deep water, but are also formed in
shallow water at and near the mouths of large rivers
and in partially enclosed seas, such as the Irish Sea.
The marine muds of the first type come under the
category of deep-water terrigenous deposits as defined

[1] *Voyage of the " Beagle,"* popular edition, 1901, p. 5.

in the *Challenger* Report.[1] They consist of the most
finely-divided fragmental material derived from the
land, carried far out to sea, and deposited near the
edge of the continental plateau and on its slopes. It
has been found by dredging that the limit between
sands and muds follows closely the 100-fathom line,
which, as before stated, is regarded as the boundary
of the continental shelf. This line is therefore desig-
nated the *mud - line* by Murray and Renard. The
downward limit of terrigenous material, though some-
what indefinite, generally occurs at a depth of about
2500 fathoms ; beyond this the pelagic abyssal deposits
are found.

The distinguishing character of muds is the presence
of a large proportion of argillaceous material of an
amorphous nature, or at any rate in such a fine
state of division that its constituent particles cannot
be distinguished, even under the microscope. The
nature of this material will be considered later. Besides
this material, however, many terrigenous muds con-
tain extremely minute particles of quartz, felspar,
mica, and other rock-forming minerals. A consider-
able proportion of organic matter and of carbonate
of lime, largely of organic origin, is also present in
nearly all samples.

The black colour of some muds is due to the
presence of ferrous sulphide (FeS) in minute globules.
In other cases the disulphide (FeS$_2$) is present, and

[1] Murray and Renard, *Report on the Scientific Results of the Voyage of H.M.S. " Challenger," " Deep-sea Deposits,"* p. 186.

imparts a blue colour to the mud. These sulphides are precipitated from iron solutions by decaying organic matter under anærobic conditions, as in the Black Sea deposits described by Andrussov.[1] According to this author hydrogen sulphide, liberated from decaying organic matter or alkaline sulphate solutions by bacterial agencies (*Bacterium hydrosulphuricum ponticum*, etc.), combines with the iron to form ferrous or ferric sulphides, the remainder effectually poisoning the water against the higher forms of life up to within 100 fathoms of the surface.

The classification of deep-sea muds commonly adopted is based primarily on colour ; this character, though at first sight apparently somewhat arbitrary, corresponds to real differences in constitution. The principal subdivisions adopted by Murray and Renard [2] are five in number : *blue mud, red mud, green mud, coral mud*, and *volcanic mud*. Of these the first is by far the commonest at the present day, and to judge by the characters of ancient marine deposits it has apparently always been so, at any rate since the beginning of the Palæozoic era.

Blue mud, when fresh, is of a bluish-grey colour : the surface layer, however, is often brown or red, owing to the presence of compounds of ferric iron, which are reduced to the ferrous state as the material accumulates. Sometimes it contains visible fragments

[1] Andrussov, " La Mer Noire," *Guide des Excursions, VIIème Congrès Géol. Internat.*, St. Petersburg, 1897, Fascicule xxix.

[2] *Op. cit.* p. 186.

of rock or of shells. The amount of calcium carbonate varies from a mere trace up to 35 per cent. In the samples collected during the *Challenger* expedition the amount of fine mud averaged 62 per cent., the rest being organic matter and mineral fragments. The blue colour is due partly to organic matter of a carbonaceous nature and partly to finely-divided iron sulphides. When fresh the mud often has a distinct smell of sulphuretted hydrogen, and this gas is undoubtedly one of the products of decomposition of the organic matter. It is supposed that the organic carbon reduces the sulphates of calcium and magnesium present in the water, and thus forms sulphides and sulphuretted hydrogen ; the latter is taken up by the iron compounds, forming sulphides of iron.

Red mud has a much more limited distribution, and is to be regarded as a rather exceptional type. It is only known to occur in any considerable quantity in two widely-separated localities, viz. off the coast of Brazil and Guiana and in the Yellow Sea. It undoubtedly consists largely of material brought down by great rivers—the Amazon and Orinoco in the one case, and the Hoang-ho in the other. This mud is of a reddish-brown colour, since all the iron is present in the ferric state and there is no iron sulphide. Calcium carbonate is found up to 25 per cent., and the mineral fragments and organic remains are of much the same nature as in the blue mud.

Green mud owes its peculiar characters, and especially its colour, to the presence of large quantities of

glauconite ; there is also present a fairly large pro-
portion of amorphous organic matter of a green
colour. The calcium carbonate varies from a mere
trace up to 50 per cent. Sometimes the glauconite
is found in a granular state of aggregation, and the
deposit then may be called greensand. This, how-
ever, differs considerably from the Cretaceous green-
sands, which are shallow - water formations. The
best-known green deposits are found on the Agulhas
bank, off the southern point of Africa. A sample·
obtained near the west coast of North America con-
sisted of almost pure glauconite.[1] The origin and
character of glauconite are discussed elsewhere (see
p. 44).

Around the oceanic islands of volcanic origin,
and in some instances near the coasts of a mainland
of volcanic character, are found fragmental deposits,
consisting for the most part of materials derived from
the denudation and decomposition of igneous rocks.
These *volcanic muds* are best known in the Western
Pacific. Near the coast they may be best described
as sandy, since they consist of visible fragments of
lava with some admixture of organic calcareous
material and a certain amount of amorphous argil-
laceous matter. Farther away the proportion of
clayey matter rapidly increases, and the deposit soon
becomes so fine in texture as to come within the
category of the muds. It always passes laterally into
normal blue, green, or other muds, or, at still greater

[1] Collet, *Les Dépôts marins*, Paris, 1908, p. 167.

depths, into an abyssal ooze. The organic con-
stituents consist of Foraminifera, Radiolaria, Diatoms,
sponge-spicules, etc.; while the inorganic particles
comprise the common minerals of the intermediate
and basic igneous rocks, together with fragments of
volcanic glass. Acid rocks are rare on oceanic islands,
especially in the Pacific, and quartz is said to be absent
from volcanic muds in this region.

The *coral muds* and *sands*, though strictly frag-
mental, are also of organic origin, and are more
conveniently treated under that heading. They are,
of course, confined to the immediate neighbourhood
of coral reefs, and are therefore only found in tropical
or subtropical seas.

The *red clay*, which is so abundant in the deeper
parts of the ocean, is a deposit of a muddy character;
it is fully described under the heading of Abyssal
Deposits (see p. 78).

Estuarine and Fresh-water Muds. — Although
muds, as has just been explained, are especially
characteristic of terrigenous deposits, laid down in
the sea at a considerable depth and generally at some
distance from land, they are also formed in shallow
water under special conditions, and may even form
part of deposits in fresh-water lakes and in rivers. All
running water carries in suspension a certain amount
of clayey material in a fine state of subdivision, which
in fresh water remains suspended for a very long time.
But when this finely-divided matter comes into con-
tact with a saline solution a physical change in its

condition is brought about, the fine particles coagulating to a kind of flocculent precipitate, which in still or gently-moving water rapidly falls to the bottom. This process occurs at or near the mouths of rivers where the fresh water first mixes with the salt sea-water, and this fact accounts for the prevalence of mud in estuaries.

This coagulation of muddy matter by salt solutions is capable of a physical explanation. In the first place, it is to be noted that the process is only brought about by electrolytes ; for it is found that colloid solutions and solutions which contain no free ions have no effect. It is evident, therefore, that the action is concerned in some way with the electrical charges on the particles ; and its effect is clearly to diminish the surface energy of the particles by reducing the area of the free surfaces. All colloid particles suspended in pure water carry electrostatic charges, and tend to repel one another, thus preserving a fine state of division. The coagulating effect of electrolytes may be referred to a removal of the charges from these particles, thus allowing them to coalesce to large masses possessing less free surface.[1]

The *estuarine muds* generally show more variation in character than those formed in deep water, and most of them contain a considerable admixture of fragmental material of much larger size ; in fact, many estuarine muds are really more correctly described as fine silts, with sufficient argillaceous material to

[1] Ramann, *Bodenkunde*, Berlin, 1911, p. 47.

estuarine and fresh-water conditions. As an example
of the kind of modern deposit which might eventually
give rise to a true marl may be mentioned the muds of
the Thames Estuary and the Medway, which contain
lime, silica, and alumina mixed in such proportions that
they are suited directly for the manufacture of Portland
cement : a similar ancient deposit is seen in the Chalk
Marl of Cambridgeshire, which lies between the Gault
and the true Chalk, and is in a chemical and minera-
logical sense also intermediate between them : it is
also largely used for cement-making, giving rise to a
considerable industry from Arlesey in Bedfordshire
to the town of Cambridge.[1] The argillaceous lime-
stones so common in the Lias were probably once soft
marly strata, though now fairly hard rocks, and the
muddy impure limestones of the Lower Palæozoic
rocks also in many of their features show a considerable
degree of similarity to marls. The fresh-water marls
of the Oligocene strata of the Isle of Wight are well
known from their numerous fossils, and the so-called
" Shell Marl " of the Fens is a deposit of shells laid
down in the meres that formerly existed in that
region.

Deep-sea Deposits.—At the present time some con-
siderable uncertainty prevails as to what precisely is
meant by deep-sea deposits, and the term is used by
different writers in a somewhat varying sense. In the
Report of the *Challenger* expedition the expression is

[1] Desch, *The Chemistry and Testing of Cement*, London, 1911,
p. 19.

used to describe all the deposits laid down in the sea
at depths greater than 100 fathoms, in contradistinction
to shallow-water deposits, which are formed at a lesser
depth. The 100-fathom line is taken as marking the
true natural line of demarcation between the continents
and the ocean basins, in the broadest sense of the term,
chiefly on the ground that the suboceanic declivities as
a rule become considerably steeper at about this depth,
and pass down with comparative suddenness to the
greatest depths. All the deposits formed in water
of a lesser depth than 100 fathoms are regarded as of
shallow-water origin, and they are, for the most part,
with certain local exceptions, of a sandy nature ; while
those formed at greater depths are essentially muddy
in character.

As an alternative it is proposed in the *Challenger*
Report to classify deep-sea deposits as *pelagic* and
terrigenous. The first class includes those in which the
constituents are derived from the sea itself, without
admixture of material from the land, and are largely
of direct organic origin. The terrigenous deposits
consist, on the other hand, of material coming from
the land, as the result either of coast erosion or of
river transportation. The terrigenous group must
obviously include the shallow-water marine deposits,
so that a further subdivision becomes necessary.

Perhaps the most satisfactory and practical classi-
fication is the compromise suggested by Murray and
Renard : the term *abyssal* is substituted for pelagic, as
expressing more clearly the relation of the deposits

to depth of water, since shallow water may exist far
from any visible land.

TERRIGENOUS   .   .   . { Shallow water.
                            { Deep water.

ABYSSAL.

The deep-water terrigenous and the abyssal groups
together correspond exactly to the deep-water deposits
of the *Challenger* Report : the following section, how-
ever, will deal exclusively with the latter group.

Abyssal Deposits.—According to the definition
just stated, the abyssal deposits include the material
now found lying on the floor of the oceans at great
depths, beyond the reach of any particles derived from
the land in the ordinary sense : they therefore consist
almost exclusively of the remains of organisms, which,
when living, floated in the sea at various depths—in
other words, they are of *planktonic* origin—with the
possible addition of volcanic and meteoric fragments,
which are carried by the waves and winds over the
surface of the open ocean. The great majority of
the planktonic organisms, both animal and vegetable,
possess no hard parts, and consequently decompose
and disappear long before reaching the ocean floor : it
is only those possessing some form of hard shell or
skeleton that can survive. These hard skeletons
consist of either silica or calcium carbonate, and the
organic abyssal deposits are therefore of either siliceous
or calcareous nature (see Fig. 7). Both silica and
calcium carbonate are, however, to some extent

soluble in water, the latter more than the former, and in both cases the solubility is increased by pressure; consequently at great depths both calcareous and siliceous structures may be completely dissolved before reaching the bottom. From the different relative solubilities of the two substances it follows that siliceous deposits are found at greater depths than those that are

FIG. 7.—SPONGE-SPICULES.

(After Murray and Philippi : " Die Grundproben der deutschen Tief-See Expedition," *Valdivia* Report.)

calcareous; and deep dredging has shown that the latter are not found below about 3000 fathoms; whereas siliceous structures have been obtained from the greatest known depths, namely, a little over 5000 fathoms. The most important of the organisms that take part in the formation of these deposits are the Foraminifera and Pteropods, both of which

have calcareous skeletons, and the Diatoms, Radio-
laria, and Sponges, which are siliceous. Since these
groups are planktonic, their geographical distribu-
tion depends for the most part on climate : some are
specially characteristic of the depths of the sea in
tropical and subtropical latitudes, while others are
essentially Arctic or Antarctic in their distribution.
Their habitat is controlled by the temperature of the
surface-waters, and not by that of the abyssal depths,
which is sensibly constant all the world over, and is
but little above the zero of the centigrade scale. In
some of the deeper regions of the ocean material of
organic origin is absent, and is replaced by a *Red Clay*,
formed for the most part by the disintegration of rocks
and minerals *in situ*.

   True abyssal deposits remained unknown up till
the year 1872, when the first specimens were dredged
by the *Challenger* expedition from the depths of the
Atlantic. During this historic voyage a great number
of deep-sea soundings and dredgings were made in all
parts of the ocean, and the material thus collected was
examined by Murray and Renard. These authors
recognised several distinct types, which will be enumer-
ated later. The results then obtained have been con-
firmed and extended by later investigations, especially
during the German deep-sea expedition of 1898-99,
by the voyages of the *Albatross* in the Pacific under
Agassiz, and by the recent work of Stanley Gardiner
in the Indian Ocean. Most of the samples obtained
on these voyages have been examined and described by

Sir John Murray and his colleagues, and our knowledge
of the deposits now forming on the ocean floor at great
depths may be considered as almost complete.[1]

Nature of the Deposits.—All the abyssal deposits
consist, as would naturally be expected, of very fine
particles, and, when wet, possess a muddy character
and appearance ; however, they are not true muds,
argillaceous matter being often wholly absent. To
connote their special character the term *ooze* is em-
ployed : only the Red Clay is a truly argillaceous
deposit. Four principal types of ooze are recognised,
namely, globigerine and pteropod oozes, which are
calcareous, and radiolarian and diatom oozes, which
are siliceous. It must be understood, however, that
numerous transitional forms exist, and in a given case it
may be difficult to say to which group the specimen
should properly be assigned.

(a) *Globigerine Ooze.*—This is one of the most

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[1] The literature of deep-sea deposits is very large and scattered,
but a summary of the most important researches, with further
references, will be found in the following : Murray and Renard,
" Deep-sea Deposits," *Report on the Scientific Results of the
Exploring Voyage of H.M.S. " Challenger,"* 1873–76, London,
1891. Murray and Philippi, " Die Grundproben der deutschen
Tief-See Expedition," *Wissenschaftliche Ergebnisse der deutschen
Tief-See Expedition,* Band x, Lief. iv, Jena, 1908. Murray and
Lee, " The Depth and Marine Deposits of the Pacific," *Mem.
Mus. Comp. Zool. Harvard,* xxxviii, No. 1, 1909. Collet, " Les
Dépôts marins," *Encyclopédie Scientifique,* Paris, 1908. Murray,
" On the Depth and Marine Deposits of the Indian Ocean, with
descriptions of the Deposit Samples collected by Mr. J. Stanley
Gardiner in 1905," *Trans. Linn. Soc. London, Zool.* xiii, 3, 1910.
Murray and Hjort, *The Depths of the Ocean,* London, 1912,
pp. 129–209.

widely distributed of all deposits, since it is estimated
to cover an area of nearly 50,000,000 square miles. It
attains its maximum development in the Atlantic, and
also covers great areas in the Pacific and Indian Oceans ;
it is known to extend as far south as latitude 60°, and
as far north as the Arctic Circle. The Globigerine
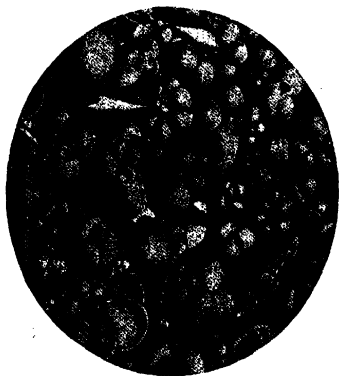
FIG. 8.—GLOBIGERINE OOZE.

(After Murray and Philippi: " Die Grundproben der deutschen
Tief-See Expedition," *Valdivia* Report.)

ooze occurs at all the medium depths of the ocean
removed from continents and islands, and is especially
developed in those regions where the surface of the
sea is occupied by warm currents ; it is found at
greater depths in tropical than in more northern or
southern latitudes. Globigerine ooze is a cream-
coloured, pink, or pale grey substance, muddy when

wet, and powdery when dry ; it consists for the most
part of the calcareous tests of Foraminifera, of which
various species of *Globigerina* are the most abundant
(Fig. 8). Many other organisms also occur, especially
pelagic mollusca—Pteropods and Heteropods—and
calcareous algæ. Siliceous organic remains are some-
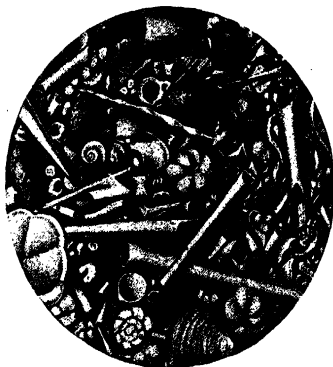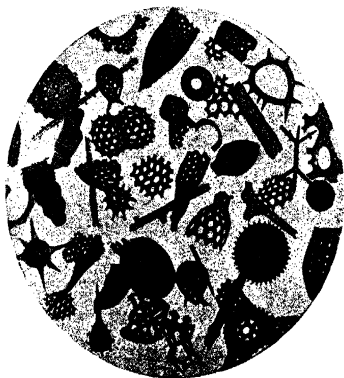

FIG. 9.—PTEROPOD OOZE.

(After Murray and Philippi : " Die Grundproben der deutschen
Tief-See Expedition," *Valdivia* Report.)

times present in considerable quantity and consist
chiefly of Diatoms, Radiolaria, and the spicules of
sponges. In the most typical samples mineral particles
are rare, and it is only in comparative proximity to
land that the common minerals of terrigenous deposits
are found ; but in samples taken in the open ocean,
far from land, only a few mineral particles of volcanic
or cosmical origin are met with : the nature of these

will be discussed in a subsequent section, since they are identical with those found in the Radiolarian ooze and in the Red Clay.

(b) *Pteropod Ooze.*—This deposit was found by the *Challenger* expedition only in the Atlantic Ocean, and especially on the central ridges of the floor of this ocean at a depth not exceeding 1400 fathoms ; it appears to be confined to tropical and subtropical regions, where Pteropods, Heteropods, and other pelagic mollusca are very common (Fig. 9). This ooze is predominantly calcareous, and contains, besides the forms just mentioned, all the distinctive constituents of Globigerine ooze, of which it may in a sense be considered a variety. A somewhat similar deposit is found at lesser depths around the shores of some tropical and subtropical islands, both in the Atlantic and in the Pacific ; but much terrigenous material is often present.

(c) *Radiolarian Ooze.*—This name is applied to all those deep-sea deposits in which the siliceous skeletons of Radiolaria are a noteworthy constituent, ranging from 30 to 80 per cent. (Fig. 10). It is usually a reddish substance, less plastic than the Red Clay, owing to the smaller proportion of argillaceous material; the mineral components apart from siliceous organisms are much the same as in the last-mentioned deposit. Some specimens contain an appreciable amount of carbonate of lime, chiefly in the form of Foraminifera. Besides skeletons of Radiolaria, the spicules of siliceous Sponges and Diatoms are also present. Radiolarian

ooze appears to be confined to great depths, and specimens were dredged up from the deepest soundings in the Western Pacific and in the Indian Ocean, where it is believed to cover a total area of about 2,000,000 square miles ; it is unknown in the Atlantic, probably because the latter ocean is not deep enough to allow of complete or nearly complete solution of

FIG. 10.—RADIOLARIAN OOZE.

(After Murray and Philippi : " Die Grundproben der deutschen Tief-See Expedition," *Valdivia* Report.)

the calcareous material, which there masks to a considerable extent the existence of the siliceous remains.

Even the most typical Radiolarian oozes can only be regarded as varieties of Red Clay specially rich in siliceous organisms : the argillaceous base of both deposits is the same, and both are equally deficient in carbonate of lime. However, numerous transitional

forms between Radiolarian ooze and Globigerine ooze
are known to exist.

Deposits rich in Radiolaria are for the most part
confined to tropical and subtropical regions (Fig. 11);
but during the voyage of the *Valdivia* a specimen
very rich in Radiolaria was dredged up in a sub-
Antarctic latitude near Bouvet Island, hence they are
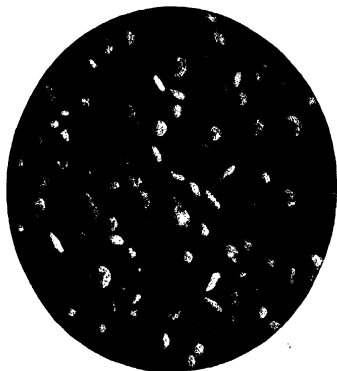
FIG. 11.—RADIOLARIA.

From Barbados.   × 20.

not exclusively confined to regions of warm surface
waters.

(*d*) *Diatom Ooze.*—This is the most limited in its
distribution of all the abyssal deposits. It appears
to be restricted to high latitudes in the neighbour-
hood of sea-ice; it covers a small area in Behring's
Sea, but attains its fullest development in the Antarctic,
where it forms a zone not far from the edge of the

permanent ice. Consequently the ooze often contains a considerable admixture of terrigenous material carried by floating ice, and it apparently grades into a normal blue mud.[1] The deposit is chiefly composed of the siliceous frustules of Diatoms, together with some calcareous Foraminifera; other constituents of organic origin are very rare. When dried, the ooze is a white or yellowish powdery substance, which when examined under the microscope strongly resembles the diatom-earth of terrestrial origin (Tripoli powder or Kieselguhr).

(e) *Red Clay*.—By far the most widely spread and most characteristic of all the abyssal deposits is that to which the name of Red Clay is generally applied. It occurs in all the deepest parts of the oceans, and in the Pacific it is estimated to cover an area of nearly 30,000,000 square miles; it is also abundant in the Indian Ocean and in the deeper parts of the Atlantic, and, in fact, it is found in almost all regions where the depth of the water exceeds 2600 fathoms. It is a chocolate-brown or more rarely light-brown or red substance, plastic when wet, but drying to a hard mass, and showing many of the characteristics of clay. Its carbonate of lime content is low, not exceeding 4 per cent.; but siliceous organisms are often abundant, and Red Clay graduates into Radiolarian ooze. Sponge-spicules are generally present, and sometimes Diatoms. The mineral components of the Red Clay show a good deal of variation according to the locality: in the

[1] Collet, *Les Dépôts marins*, Paris, 1908, p. 112.

South Pacific the most abundant constituents are minute fragments of basic volcanic rocks; in the North Pacific pumice prevails; while in the South Atlantic quartz is dominant, with some felspar and mica. These particles are for the most part derived from the decomposition and decay of floating fragments, ejected by volcanic eruptions, some of which may have been submarine. The fact must be strongly emphasised that Red Clay has no definite composition, but varies according to the source from which the material is derived; it is believed that the eruption of Krakatoa in 1883 strongly influenced the composition of the abyssal deposits of the Indian Ocean. In some parts of the Atlantic, again, are found grains of sand which must have been carried by Harmattan winds from the deserts of Africa. Other substances common in samples of Red Clay are crystals of phillipsite—a mineral of the zeolite group—and rounded or botryoidal nodules of manganese dioxide. This latter substance is believed to be a product of the decomposition of volcanic material. These manganese nodules are scattered over the floor of the deeper parts of the oceans in great quantity, and are often associated with vast numbers of sharks' teeth and the ear-bones of whales. The abundance of these organic remains indicates that at the greatest depths the deposits form with extraordinary slowness, since remains of extinct species are often dredged up along with those of existing forms, showing that since Tertiary times the thickness of Red Clay formed has

been insufficient to bury them completely. Apart from these larger constituents, the Red Clay is summed up by Murray and Philippi [1] as a decomposition product of aluminous silicates derived partly from the decomposition of rock fragments spread over the oceans by various sub-aerial and volcanic agencies, and partly from weathering in place of the rocks forming the sea floor : from this point of view it is to be regarded as a residual deposit from which most of the carbonate of lime and silica have been removed by solution, and it has much in common with the "residual red clay" of American geologists.

From a detailed study of abyssal deposits it appears clear that the differences between the several varieties arise to a large extent from the varying solubility of their constituents. [2] The solubility of nearly all substances in water is increased by pressure, partly because water can under higher pressure hold more gases in solution, and these gases, especially carbon dioxide, assist in the solution of the solids. Hence the solubility both of calcium carbonate and of silica is increased at great depths. But since calcium carbonate is more soluble than silica, the process is a differential one : at a certain depth all the calcareous organisms will be dissolved, while the siliceous skeletons will continue to sink, and may eventually reach the floor of the ocean.

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[1] " Die Grundproben der deutschen Tief-See Expedition," *Wiss. Ergebn. der d. Tief-See Expedition*, x, iv, p. 137.
[2] Kendall, *Rep. Brit. Ass.*, 1896, p. 789.

The purely inorganic material is even less soluble than the Radiolaria and sponge-spicules, and reaches the bottom in greatest quantity. Where the depth is not too great (less than 2500 fathoms) the deposit consists of a mixture of calcareous and siliceous organisms, with the material of the Red Clay. The two latter, being much less in amount, are, as it were, masked by the abundance of the former, and the deposit is correctly described as a calcareous ooze. But at greater depths only the siliceous and inorganic portions remain, and form a Radiolarian ooze or a Red Clay, according to the proportions in which these two constituents are present. The Red Clay is therefore the most insoluble residue of the planktonic and inorganic material. The fact that Radiolaria are in some cases relatively more abundant at the very greatest depths than at somewhat higher levels has not yet been explained.

CHAPTER III

CHEMICAL DEPOSITS

UNDER this heading are included a series of deposits of which the origin can be referred directly to processes of a physico-chemical character, chief among these being *crystallisation* and *precipitation*. In the strict sense of the term, therefore, they are not sediments ; nor do they, as a rule, present the markedly laminated stratification characteristic of these deposits, being, on the other hand, frequently distinguished either by a radial fibrous or by a concentric concretionary structure.

Although substances belonging to this class often occur as irregular masses, the chemical deposits are usually found regularly interbedded with fragmental or organic sediments, most of the latter having been deposited in lakes or in isolated portions of the sea, while the former are usually of terrestrial origin.

In certain chemical deposits it has been found that precipitation is determined by the work of bacteria and other lowly organisms. Familiar examples are the formation of iron ores in lakes, and the separation

of siliceous or calcareous sinter from the waters of
hot springs, to which reference will be made later.

The most important of the physico-chemical pro-
cesses that give rise to deposits of the nature here
described is undoubtedly evaporation. This takes
place extensively in salt lakes or in partially isolated
marine basins, the products thus formed being com-
prised under the general heading of *salt deposits*.
The occurrence of such deposits is a distinguishing
characteristic of the desert facies of deposition. Since
the determining factors of this facies are a small rain-
fall and a high temperature, only rarely can a similar
process take place under temperate conditions.

The chemical deposits are most conveniently
classified according to their composition. The most
important compounds of this class are the chlorides
and sulphates of sodium, magnesium, calcium, and
potassium ; nitrates are less abundant, sodium nitrate
alone occurring in large masses. Bromides and iodides
are widely distributed, but in small quantity, while
boron compounds are locally abundant. Calcium car-
bonate in various forms is one of the commonest of
rock-forming substances, and dolomite, the double
carbonate of calcium and magnesium, is also common.
Alkaline carbonates, on the other hand, occur only
under certain special conditions. Calcium and mag-
nesium carbonate deposits of organic origin are
excluded from this group and will be treated else-
where. Silica also occurs in masses formed by the
evaporation of its solution in certain thermal waters

and sometimes forms large deposits. Considered thus the chemical deposits may be divided into seven groups as follows :

Chlorides.	Nitrates.
Sulphates.	Carbonates.
Borates.	Silica deposits.

Iron deposits.

On account of their close association in nature it is convenient to consider the chlorides and sulphates under one heading.

Chlorides and Sulphates. — The most important salt deposits occurring on a large scale in nature are the chlorides and sulphates of sodium, potassium, magnesium, and calcium. These sometimes form simple salts, as sodium chloride and calcium sulphate ; but they are also found in the form of double salts, or even as more complex combinations.

The most abundant of them are formed by the evaporation of the waters of salt lakes or of the sea under special conditions. Since the water of the open sea is nowhere saturated with the salts dissolved in it, it is clear that salt deposits cannot be formed in the sea at the present time ; and there is no reason to believe that the proportion of salts in the open sea was ever higher in the past than at present.

The composition of sea-water is not everywhere constant. In tropical climates rapid evaporation raises the proportion of salts. In the Mediterranean it is notably higher, owing to the enclosed character of this basin, combined with a high temperature. Since

there is a constant inflowing current of sea-water
through the Straits of Gibraltar and no outward diffu-
sion to restore equilibrium, the salts must become
concentrated. On the other hand, in the Baltic,
which is a nearly enclosed basin, with a cool climate
and comparatively little evaporation, a large influx
of river - water tends to produce an outward
current through the openings between Denmark and
Scandinavia : hence the salinity of the Baltic is
very low.

According to analyses of samples from all over the
world collected during the voyage of the *Challenger*,
one hundred parts of sea-water from the open ocean
contain on an average 3.44 parts of dissolved matter,
which is made up as follows :

Sodium chloride	.	.	.	77.758	per cent.
Magnesium chloride	.	.	.	10.878	,,
Magnesium sulphate	.	.	.	4.737	,,
Calcium sulphate	.	.	.	3.600	,,
Potassium sulphate	.	.	.	2.465	,,
Magnesium bromide	.	.	.	.217	,,
Calcium carbonate	.	.	.	.345	,,
				100.000	

A striking point in the above figures is the small
proportion of calcium carbonate, the explanation
being that it is taken up by animals and plants as fast
as it is brought in by rivers. For the purposes of the
present discussion it may be neglected. The pro-
portions of bromine (and iodine) are also extremely
small, but their presence is significant in connection

with the origin of certain salt deposits, as will appear later.

Although a concentration of dissolved salts to such an extent as to give rise to solid deposits is impossible in the open sea, it may take place under special conditions in partially enclosed areas having limited communication with the main sea. Under such geographical conditions and where high temperature causes strong evaporation, while a small rainfall limits the supply of fresh water, the concentration of salts may be carried to the point of saturation and precipitation. A classical example is the nearly circular Kara Boghaz, an inlet on the eastern side of the Caspian Sea, which probably owes its origin to a subsidence on one side of the folded chain of the Caucasus. The waters of this gulf have a composition very different from that of the Caspian Sea. It is true that the latter is not in communication with the open ocean, and that its waters vary in composition. This is to be accounted for by the fact that at the northern end the climate is cold for most of the year, and many rivers flow in, whereas the southern end comes within the influence of the high temperature and low rainfall of the desert zone. Nevertheless the mean composition is not far removed from that of the open ocean.

The following table shows the salt-content in 1000 parts of water of the surface waters of the Caspian and of the Kara Boghaz respectively : [1]

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[1] Roth, *Allgemeine chemische Geologie*, Berlin, 1879, p. 465.

			I. Caspian.	II. Kara Boghaz.
Sodium chloride	.	.	8.116	83.284
Potassium chloride	.	.	.134	9.956
Magnesium chloride .	.	.	.612	129.377
Magnesium sulphate .	.	.	3.086	61.935

These analyses furnish clear evidence that a great concentration of salts of sodium and magnesium has taken place in the waters of the gulf. The lower layers of the water of the Kara Boghaz are still richer than the sample. Under these circumstances it is not surprising that deposits of sodium and magnesium salts are now being formed on the floor of the gulf. The phenomenon may be explained thus. The gulf, which is fairly deep, is separated from the Caspian by a narrow and shallow strait. A hot and dry climate promotes active evaporation ; consequently a continual current of water runs in through the strait to supply the loss by evaporation, keeping the level constant. Hence there is a continual addition of salts, and the strait is too shallow to permit of diffusion outwards at a lower level.

The exact nature of the salts deposited varies from time to time, according to temperature, since the equation

$$MgSO_4 + 2NaCl \leftrightarrows MgCl_2 + Na_2SO_4$$
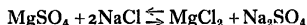
is reversible.[1] At present the water is saturated for sodium compounds, but not for magnesium salts ; hence the deposits consist of sodium chloride and sulphate (common salt and Glauber's salt respect-

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[1] Kurnakoff, *Zeits. für prakt. Geologie*, 1905, p. 189.

ively). Magnesium and potassium salts are not formed.

Such highly specialised conditions are not essential for the formation of the considerable deposits of rock-salt and gypsum that are found along the shores of the Red Sea and Gulf of Suez, and even on islands in the same ; these appear to be largely due to the desiccation of sea-water transported by the wind in the form of spray and froth.[1] In the same region large masses of crystalline gypsum are supposed to be due to evaporation of sea-water brought to the surface by capillarity through sand, the evaporation not being sufficiently complete to crystallise the sodium chloride. Where the sand is calcareous, a metasomatic replacement of calcium carbonate by calcium sulphate seems to occur, by which organic remains are destroyed and raised coral reefs converted into gypsum.

Under certain conditions salt may be carried by wind for long distances inland in the form of fine dust or as spray from the sea. During the great storms of 1839 great quantities of salt blown from the Irish Sea and amounting to tons per acre were spread over Lancashire and Yorkshire ; and even beyond the Pennine Hills the trees were white with salt. The salinity of the Dead Sea has even been attributed to chlorides brought by wind from the Mediterranean ! In the desert of Rajputana in north-western India many temporary lakes are formed

[1] Ackroyd, *Geol. Mag.*, 1901, p. 445.

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in·the rainy season. During the dry season these
become concentrated to small pools of brine. It
has been proved experimentally that during the dry
season, when strong winds blow persistently from
the south-west, great quantities of salt are carried
inland from the Runn of Cutch and from the coast,
which the north-easterly winds at other seasons are
not strong enough to blow back again. Analyses of
the air during the dry season showed that as much
as 130,000 tons of salt were annually carried by this
means into Rajputana. This salt is dissolved by
the rainfall and carried down into the lakes, where
by evaporation it gives rise to salt deposits.[1]

Salt Deposits of existing Lakes.—In the arid regions
of the world salt-lakes exist at the present day, and
have in many cases given rise to characteristic deposits.
Some of these are distinguished from salt deposits
of marine origin by the presence of considerable quan-
tities of sodium carbonate ; while others are character-
ised by an abundance of sulphates of sodium and
magnesium. In almost all cases gypsum or anhydrite
is also deposited.

The chemical analysis of the waters of salt lakes
gives little information of any value, since the com-
position varies within very wide limits. It is affected
both by the depth below the surface and by the
proximity of fresh-water tributaries. Still greater are
the variations that depend on changes of temperature.
The solubility of nearly all natural salts, except

[1] Holland, *Proc. Liverpool Geol. Soc.*, vol. xi, 1912, p. 227.

calcium sulphate, increases with the rise of tempera-
ture ; hence if the solution is at, or near, saturation-
point, salts may be deposited in winter and redis-
solved in summer. The solubility of calcium sulphate,
on the other hand, is lowered by a rise of temperature,
and it is therefore deposited in summer. These facts
account for the rapid alternation of layers of rock-salt
and gypsum or anhydrite, which are so common in
salt-beds and are called " year-rings " by the German
miners.

The following table of analyses of the waters of
some typical salt-lakes serves to show the wide varia-
tions of composition that are possible ; these are for
the most part extreme cases, in which the water is
saturated, at any rate for some of the salts, and de-
position is actually taking place.

SALT-CONTENT OF THE WATERS OF CERTAIN LAKES
IN PARTS PER 1000.

	Dead Sea.	Great Salt Lake, Utah.	Lake Elton.	Lake Urmiah, Persia.	Carson Lake, Nevada.
Sodium chloride	63.86	118.63	38.3	190.47	64.94
Magnesium chloride	163.67	14.91	197.5	5.22	..
Calcium sulphate	.78	.86	..	1.81	..
Magnesium sulphate	..	..	53.2	8.00	..
Sodium sulphate	..	9.32	..	..	13.76
Sodium carbonate	..	..	..	..	29.25

Note.—In some cases a small amount of potassium salts is recorded :
this, as well as other less common constituents, is here omitted for the
sake of simplicity.

These figures indicate the existence of two fairly well-marked types, viz.: (1) *salt lakes proper*, with dominant chlorides, of which the Dead Sea is a good example ; (2) *bitter lakes*, with sulphates and alkaline carbonates, *e.g.* Carson Lake, Nevada. Lake Elton is intermediate between these two groups, being rich in both chlorides and sulphates.

The Dead Sea and Great Salt Lake.—The physical history of these lakes has been worked out in great detail. They originated as fresh-water lakes with a normal outflow. Climatic changes supervened, causing a diminished inflow and increased evaporation. In consequence, the lakes lost their outlets and became increasingly concentrated, and are now depositing salts, at any rate at certain seasons of the year. The great difference they show in the relative amounts of the salts held in solution is due to the different composition of the material brought in by the rivers in each case ; and this, of course, is determined by the different mineralogical constitution of the rocks from which it is derived.

It has been shown that the waters of the river Jordan, which is the principal affluent of the Dead Sea, are unusually rich in dissolved mineral matter, because it flows through a region largely composed of salt-bearing rocks of Cretaceous and Eocene age. Besides this source of supply there are in the neighbourhood many mineral springs, some of which are hot and are connected with the vulcanism that accompanied the subsidence of the area in which the Dead

Sea lies (the Great Rift Valley). Owing to great variations in composition of samples of water from the Dead Sea, obtained at considerable depths, it is believed that there are subaqueous mineral springs, some of which also yield bituminous products (hydrocarbons). A remarkable feature of the water is the presence of a large proportion of bromine, calculated by Lartet to be equivalent to 5 parts of magnesium bromide per 1000 of water.[1]

As shown by the analysis quoted above, the waters of the Dead Sea are extraordinarily rich in magnesium chloride. Since this salt is much more soluble than sodium chloride, and the water is not yet saturated with it, compounds of magnesium are not being deposited. On the other hand, since the presence of magnesium chloride diminishes the solubility of sodium chloride, in accordance with the law of the influence of the common ion, the water is saturated for sodium chloride. Consequently crystals of common salt, together with gypsum, are abundantly present in the muddy deposits now being laid down on the floor of the lake, and all the sodium

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[1] The following are some of the most important memoirs on the geology of the Dead Sea : Lartet, *Exploration géologique de la Mer Morte*, Paris, 1877, and *Bull. Soc. Géol. France*, (2), 22, 1865, pp. 420-63. Blanckenhorn, *Entstehung und Geschichte des Todten Meeres.* Hull, *Memoir on the Physical Geology and Geography of Arabia Petræa, Palestine, and adjoining Districts*, London, 1886. Russell, " The Jordan-Arabah Depression and the Dead Sea," *Geol. Mag.*, 1888, p. 337. For a summary and further references see Suess, *Das Antlitz der Erde*, vol. i, pp. 479-84 ; in the French translation additional references are given.

and calcium salts brought in by the Jordan and other rivers are at once precipitated.

The principle here enunciated is very important in the study of salt lakes ; and it accounts for the fact that common salt is now being deposited in many lakes in the waters of which very different proportions of this salt are contained, since the saturation point for any one salt is controlled by the proportions of other salts present in the solution.

In the Great Salt Lake of Utah, however, the proportion of magnesium chloride is much less, so that more sodium chloride can be held in solution (see analysis on p. 99). On the other hand, sulphates are present to an extent sufficient to impart to the water some of the characters of a bitter lake. This lake, which covers an area of about 2000 square miles, is very shallow, its maximum depth being about 50 feet. It lies in the arid region of the Great Basin, and is the relic of a once much larger fresh-water lake, evidence of whose former existence is afforded by the character and composition of the ancient high-level beaches that surround it at varying heights up to 1000 feet above the surface of the present lake. It occupies the lowest part of a great plain largely covered by saline deposits, and is now depositing great quantities of rock-salt.[1]

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[1] The former history of this lake has been worked out by the U.S. Geological Survey ; see Gilbert, " Contributions to the History of Lake Bonneville," *Ann. Rep. U.S. Geol. Survey*, vol. i, 1890, p. 168, and " Lake Bonneville," *Monograph I, U.S. Geol. Survey*, 1890.

Ancient Salt Deposits.—Among the salt deposits of the older rock-series, common salt, gypsum, and anhydrite are by far the most abundant ; in fact, only few cases are as yet known where these are accompanied by a considerable development of salts of potassium and magnesium : of most importance is the salt deposit of Stassfurt in Germany, in which, besides rock - salt, gypsum, and anhydrite, numerous compounds of potassium and magnesium are found, together with iodides, bromides, and borates. The general character of the salts suggests that they were formed by the complete evaporation and desiccation of great volumes of sea-water under somewhat similar conditions to those now prevailing in the Kara Boghaz. This question has been studied on the experimental side during the monumental researches of Van't Hoff and his pupils.[1]

Van't Hoff investigated the course of crystallisation of sea-water at various temperatures, and especially at 25° C. He employed an artificial sea-water having the following composition :

Water	1000 parts.
Sodium chloride. . . .	24.0 ,,
Potassium chloride . . .	11.5 ,,
Magnesium chloride . . .	40.7 ,,
Magnesium sulphate . . .	20.0 ,,

[1] Van't Hoff, *Zur Bildung der ozeanischen Salzablagerungen*, Brunswick, 1905, and *Untersuchungen über die Bildungsverhältnisse der ozeanischen Salzablagerungen*, etc., Leipzig, 1912. For an abstract in English see Armstrong, *Rep. Brit. Assoc.*, Glasgow, 1901 ; also Clarke, " The Data of Geochemistry," *Bull. U.S. Geol. Survey*, 1916, pp. 221-28.

He found that this solution on evaporation at the
atmospheric pressure gave rise to a large number of
salts of sodium, potassium, and magnesium, often
double or even triple salts, which were exactly similar
to those actually found at Stassfurt. For the purposes
of this investigation the lime salts were omitted, since
calcium sulphate is so much less soluble than those
above-mentioned that it would have been wholly
removed from the solution before the others began to
crystallise. But the crystallisation of calcium sulphate
was studied separately, with special reference to the
conditions regulating its occurrence as gypsum and
anhydrite respectively. A pure solution of calcium
sulphate will crystallise as gypsum up to 60° C., and
above this as anhydrite, but from sea-water, natural or
artificial, anhydrite separates at all temperatures above
25° C. Hence the presence of anhydrite in natural
salt-beds gives us valuable information regarding the
temperature which prevailed at the time of its crystal-
lisation.

The general succession of minerals found in the
Stassfurt salt-beds is the following : [1] in the lowest
part of the shaft is about 200 metres of rock-salt, with
thin partings of anhydrite (the *year-rings* of the
German miners) ; 7 millimetres of anhydrite, and
8 or 10 centimetres of rock-salt alternately ; then
follows the polyhalite region, which is characterised

    [1] Ochsenius, *Zeits. für prakt. Geol.*, 1905, p. 167. Van't Hoff,
op. cit. Doelter, *Petrogenesis*, Brunswick, 1906, p. 243 ; *ibid.*,
Physikalisch-chemische Mineralogie, Leipzig, 1905, p. 228.

by sodium chloride, magnesium sulphate, and potassium sulphate. This layer is about 60 metres thick, and is sharply marked off above and below. It is overlain by the kieserite region, also about 60 metres thick, which contains rock-salt, kieserite, carnallite, and magnesium chloride, with very little anhydrite. The highest division is the carnallite region, 30 metres thick, with carnallite, rock-salt, kieserite, sylvite, bischofite, and other less common minerals. Resting unconformably on the salt deposits comes a bed of impervious clay, to the presence of which is doubtless due the preservation of such highly soluble salts. The following table shows the chemical composition of the most important minerals found here :

Rock-salt	.	.	NaCl.
Sylvite .	.	.	KCl.
Carnallite	.	.	$KCl . MgCl_2 . 6H_2O.$
Bischofite	.	.	$MgCl_2 . 6H_2O.$
Kieserite	.	.	$MgSO_4 . H_2O.$
Polyhalite	.	.	$K_2SO_4 . MgSO_4 . 2CaSO_4 . 2H_2O.$
Kainite	.	.	$KCl . MgSO_4 . 3H_2O.$
Anhydrite	.	.	$CaSO_4.$
Gypsum	.	.	$CaSO_4 . 2H_2O.$

Besides these, many other minerals have been found in small quantities, and the Stassfurt salts are now the principal commercial source of compounds of iodine and bromine. Borates also occur to a considerable extent. The Stassfurt salt-beds are now exploited commercially on a large scale, and they are the chief source of potash salts for manufacturing and agricultural purposes. Kainite, carnallite, and

other potash salts are also found at Kalusz in Galicia and at Aussee in Austria.[1]

Observation and experiment, therefore, combine to show that the Stassfurt salt deposits were formed by evaporation of sea-water on a large scale, and this process must have culminated in complete or nearly complete desiccation, since potassium and magnesium salts are not thrown down from normal sea-water until the volume is diminished by about 97 per cent. In other cases, however, the desiccation seems to have been less complete, since thick beds of rock-salt and gypsum or anhydrite, and of the two latter minerals alone, are known in many localities without any accompanying deposits of potassium and magnesium salts. In many cases these *incomplete* salt deposits have doubtless been formed in continental salt lakes ; but some of them are too thick to admit of this explanation of their origin, owing to the great size and depth of the lakes which would have been necessary.

As a result of a boring for coal potash salts were located in 1904 at Wittelsheim in the south of Alsace, at depths varying from 650 to 1000 metres. The principal bed has an average thickness of 4 metres and contains about 30 per cent. of potassium chloride. The less important bed lying about 25 metres higher in the series, though thinner and of less extent, runs to about 35 per cent. of potassium chloride. In both beds the chief salt is sylvite, and the salts are of considerably

[1] Görgey, *Tscherm. Min. Pet. Mitt.*, vol. xxviii, 1909, p. 334, and vol. xxix, 1910, p. 148.

higher grade than those of Stassfurt. Since the return
of Alsace to French control a highly important industry
has sprung up here, and the same or other beds have
been exploited in many concessions.

Beds of potash salts have also been worked in the
salt district of Cardona in Catalonia, especially near
the town of Suria, in Tertiary strata. They include
carnallite and sylvite, but owing to marked disturbances
of the strata and steep dips the extent of the beds is
still somewhat uncertain.

The greatest salt deposit known is that at Speren-
berg, near Berlin. A bore-hole put down at this
place passed through more than 4000 feet of rock-
salt without reaching its base. The lateral extent
of this bed is unknown; but since it is generally
assigned to the same age as the salt-beds of Stass-
furt and Leopoldshall (viz. Zechstein, or Upper
Permian), they are possibly continuous. Again, a
bed of rock-salt having a thickness of 1200 feet has
been traced for 500 miles in Austrian Poland, and is
extensively mined at Wieliczka. Salt-beds of great
extent are also found at Parajd in Transylvania. These
deposits are of Miocene age, forming part of the
Vindobonian series, which corresponds to the second
Mediterranean stage of Suess. The salt-beds are
associated with ozokerite and petroleum.

In these and other cases a marine origin seems
to be established, although Walther [1] is inclined to
refer every instance to evaporation of salt lakes lying

[1] *Das Gesetz der Wüstenbildung*, Berlin, 1900, pp. 140-56.

in enclosed basins, without connection with the sea, and under the influence of a desert climate, with its concomitant high degree of evaporation and small inflow of drainage water. The presence of such great quantities of soluble salts is attributed by Walther to the high original salt-content of sedimentary rocks of marine origin, which he estimates at 1 per cent. of their total weight. This salt, washed out of sedimentary rocks during their denudation, and dissolved by the waters which formed the lake, would on evaporation produce a high degree of salinity. A process of this kind has certainly been operative in some modern instances, as, for instance, in the Dead Sea and in the Great Salt Lake of Utah, but it is insufficient to account for enormously thick salt deposits such as those described.

In the British Isles rock-salt is found in the Permian and Trias, where it is always associated with red marls and gypsum and anhydrite, and shows every evidence of having been formed by evaporation of salt lakes into which large quantities of wind-blown dust were being transported. In many localities where rock-salt does not now actually occur, casts or moulds of cubic crystals of this mineral in the marl afford evidence of its former existence. Remains of marine organisms are unknown in these strata, and in fact occasional footprints of reptiles are the only indications of life. In the neighbourhood of Middlesbrough, on both sides of the Tees, a bed of rock-salt, varying in thickness from 80 to 115 feet, is now

extensively worked at a depth of from 1200 to 1500 feet from the surface : it is generally assigned to the Bunter division of the Trias.[1] All the other salt-beds worked in Britain are of Keuper age, forming inter-calations in the Upper Keuper marls ; these marls are 2000 feet thick in places, and always contain gypsum either in isolated crystals or in layers (satin-spar and alabaster). The most important localities for British salt deposits are between Droitwich and Stoke in Worcestershire, in Cheshire, and at Carrick-fergus, near Belfast.[2] In Cheshire the salt occurs in two principal beds about 90 and 105 feet thick re-spectively, separated by about 30 feet of clay or marl with veins and layers of salt and gypsum.[3] At North-wich the salt is worked by shafts, but in other places it is pumped up as brine. At Carrickfergus the aggregate thickness of the salt-beds is nearly 150 feet. The Triassic strata of the Eden valley and of the northern plain of Cumberland include red marls, with gypsum and occasional thin beds of rock-salt.

Borings at Hartlepool have shown that the Mag-nesian Limestone of that district contains, where protected by the overlying red beds, large quantities of calcium sulphate, mainly in the form of anhydrite.

[1] Wilson, " The Durham Salt District," *Quart. Journ. Geol. Soc.*, xliv, 1888, p. 761. This author assigns the salt-bed to the Keuper, but this is probably incorrect. In the complete absence of fossils the question cannot be definitely settled.

[2] " Rock-Salt and Brine," *Special Rep. Min. Res. of Gt. Britain, Geol. Survey*, 1921.

[3] A. F. Calvert, *Salt in Cheshire*, London, 1915.

Where, however, the Magnesian Limestone has been divested of its protective covering of Permian and Triassic red marls, the anhydrite has been converted to gypsum and removed by the action of percolating waters. The porous condition in which the formation was left by the removal of the sulphates laid it open to the formation of hard calcareous breccias with segregated magnesian carbonate in a finely divided condition. The subsequent removal of the latter in solution brought about dedolomitisation in parts of the formation.[1]

The home resources of gypsum (including alabaster) are abundant. The average annual output in the United Kingdom in the three years 1912–14 amounted to close on 380,000 tons and was derived from the Permian, Triassic, and Jurassic formations. The only localities in England where the variety known as Alabaster is worked are Fauld, near Sudbury (Stafford-shire), and Chellaston (Derbyshire).[2]

Borates.—Besides their occurrence in the Stass-furt salt deposits, compounds of boron have been described as deposits from the waters of lakes and from hot springs, as in Tuscany. The latter are clearly of volcanic origin ; and it is noticeable that the borax lakes of Western America occur in a region of recent volcanic activity. No doubt the ultimate

[1] Trechmann, *Quart. Journ. Geol. Soc.*, vol. lxix, 1913, p. 184.
[2] *Special Rep. Min. Res. Gt. Britain*, vol. iii. " Gypsum and Anhydrite," *Mem. Geol. Survey*, 2nd edition, 1918. B. Smith, *Quart. Journ. Geol. Soc.*, vol. lxxiv, 1918, p. 174.

source of boron compounds is in all cases volcanic or pneumatolytic.

In the Great Basin region of Nevada and California there are several shallow lakes or dried-up lake basins where borax occurs in association with gypsum, anhydrite, sodium carbonate and sulphate, and many other minerals. Searles Marsh, a shallow lake or swamp, occupying a hollow in the middle of an alkali plain in San Bernardino county, California, is nearly filled by deposits of sodium carbonate and sulphate, rock-salt and borax, together with mud and much volcanic sand. Here the evidence of recent vulcanicity is clear. In the Calico district of the same county a thick bed of colemanite (calcium borate) is extensively worked as a source of borax. This is clearly a beach deposit formed on the shores of a lake. Tincal or sodium borate occurs in lakes in Tibet.

Nitrates.— The most important deposit of this class is the well-known Chile saltpetre or nitrate of soda of South America. This is found in the desert region of the Pacific coast, especially in the provinces of Tarapacá and Antofagasta in Chile. The nitrate area is several miles inland, and rises to a height of over 4000 feet above sea-level. It stretches from north to south for about 260 miles. An examination of the workings discloses three successive layers :

(1) Fine, loose sand : 8 or 10 inches.
(2) Hard crust, consisting of common salt, gypsum, magnesium salts, and various mineral fragments : 6 to 10 feet.
(3) Impure sodium nitrate (*caliche*) forming the base.

The origin of the nitrate has given rise to much discussion : Ochsenius [1] suggests that beds of rock-salt were converted into sodium carbonate by carbon dioxide of volcanic origin ; this he supposes to react with ammonia salts derived from overlying guano-beds, so as to form nitric acid, which, by combining with the soda, yields sodium nitrate. Plagemann,[2] on the other hand, has referred its origin to the bacterial decomposition of guano : the ammonia compounds first produced give place to nitric acid, which combines with lime in the underlying soil. The calcium nitrate thus formed reacts with sodium sulphate, forming calcium sulphate and sodium nitrate, thus :

$$Ca(NO_3)_2 + Na_2SO_4 = CaSO_4 + 2NaNO_3.$$
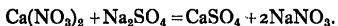
The sodium sulphate required for this reaction is assumed to be in the soil, as is very commonly the case in dry climates. The chief objection to the theory, however, is the absence of phosphates in the nitrate deposits. Phosphates are abundant in guano, and since they are insoluble in water their absence here is difficult to explain.

Another theory traces the origin of the nitrate deposits to the decomposition of great masses of sea-weed, left stranded by the uplift of the land. On this view the ammonia compounds which form first give rise to nitric acid, the rest of the process being as before. This theory is supported by the absence

[1] Ochsenius, *Die Bildung des Natronsalpeters*, 1877.
[2] Plagemann, *Die Dungstoffindustrie der Welt*, Berlin, 1904.

of phosphates and the presence of much iodine, a characteristic constituent of seaweeds.

Carbonates. — The characteristic constituent of the so-called *natron lakes* is sodium carbonate ; but this compound is always accompanied by sodium chloride and sodium sulphate, together with other carbonates and sulphates. The deposits of such lakes are of a peculiar character, and often include *trona,* $Na_2CO_3 . NaHCO_3 + 2H_2O$, and *gaylussite,* $CaCO_3 . Na_2CO_3 + 5H_2O$. Natron - lakes, or soda-lakes, as they are called by many American writers, occur in Mexico and on the plateau of Nevada in the United States. Some of the lakes in the oases of western Egypt and the Sahara, and even in the Nile valley, are of similar nature.[1] Analyses [2] of the water of small lakes in the neighbourhood of Mt. Ararat show extraordinarily high salt-contents, amounting in one case to 239 parts of sodium carbonate and 53 parts of sodium sulphate in 1000 parts of water.

Calcareous Sinter.—Almost all natural waters contain calcium carbonate in solution. The solubility of this salt is greatly increased by the presence of carbon dioxide, since, under these circumstances, a bicarbonate is formed of higher solubility than the normal salt, thus :

$$CaCO_3 + CO_2 + H_2O = CaH_2(CO_3)_2.$$

[1] Willm, *Comptes Rendus*, vol. liv, 1862, p. 1224.
[2] Abich, *Bull. Acad. St. Petersburg*, 5, 1847, p. 118, quoted by Roth, *Allgemeine und chemische Geologie*, Berlin, 1879, p. 486.

· The bicarbonate, however, is unstable, and is
easily decomposed, even by evaporation of the solution
at ordinary temperatures; consequently the less
soluble carbonate may be re-formed and deposited.
Further, the solubility of carbon dioxide in water is
increased by pressure, so that springs issuing from
a deep-seated source, often at a temperature above
that of the air, immediately become saturated and
deposit their excess of calcium carbonate in the solid
form; thus many hot springs, éspecially in volcanic
regions, give rise to great masses of calc-sinter, or
travertine, as in Auvergne, and on a much larger scale
in Italy, especially in Tuscany and near Rome, *e.g.* the
famous travertine deposits of Tivoli.[1] Here, accord-
ing to Lyell, the river Anio has cut a deep gorge
through a great mass of travertine, produced, as he
supposes, in a former lake. The river is now deposit-
ing similar material in the gorge, especially in the
neighbourhood of the cascade, where icicle - like
structures are in process of formation. The travertine
shows a remarkable development of concentric and
botryoidal structures, resembling those of oolitic and
pisolitic limestones; while in some cases nearly
spherical concretionary masses have been formed
with a diameter of six or eight feet, and consist of
innumerable thin concentric layers of calcium carbonate.

The well-known Sprudel of Karlsbad, in Bohemia,

[1] For a graphic account of these and other calcareous deposits
from hot springs, see Lyell, *Principles of Geology*, 11th edit.,
1872, pp. 396-404.

is a hot spring which issues at a temperature of 163° F. The waters are fairly rich in sulphate and chloride of sodium, and there is some carbonate of lime. Until comparatively recently the carbonate of lime separated from the water by the action of calcareous algæ,[1] giving rise to banded travertine and to well-developed pisolite, in which the grains are often one-eighth of an inch in diameter. They consist of aragonite, and under the microscope show well-marked concentric layers, but no radial structure, the aragonite crystals being arranged tangentially. At the present time the springs are maintained under such artificial conditions that the deposits are no longer being formed. A pisolitic travertine of like nature is being deposited by the springs at Vichy (Fig. 12).

Calcareous deposits of a somewhat similar character are extensively developed around some of the desiccated lakes of the Great Basin region of western America. The best example is afforded by the shore deposits of Lake Lahontan[2] in northern Nevada. This lake was formerly fed by streams bringing in a large quantity of dissolved calcium carbonate ; and this substance now constitutes great sheets and terraces along the former shores of the lake, and on the buttes which were once islands in it. According to Russell, there are in this district three distinct types of cal-

[1] Cohn, " Über die Algen des Karlsbader Sprudels," *Abh. Schles. Ges. Vaterländ. Kultur*, 1862, p. 65. Vater, *Zeits. für Kryst.*, vol. xxxv, 1902, p. 149. Suess, *Geogr. Journ.*, 1902, p. 517.
[2] Russell, " Sketch of the Geological History of Lake Lahontan," *Mon. U.S. Geol. Survey*, xi, 1885.

careous deposit, or *tufa*, which he calls *lithoid*, *thinolitic*,
and *dendritic* respectively. The lithoid tufa is grey
and compact, and much more stone-like than the
others; it often contains shells which indicate that
it was formed in fresh water. The thinolitic tufa,
although consisting solely of calcium carbonate, is
said to be pseudomorphous after the mineral gaylussite
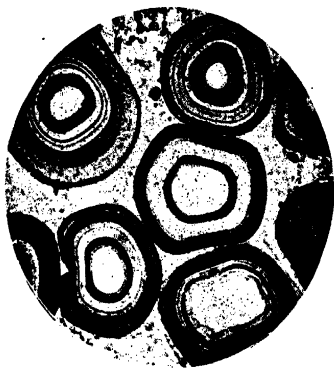
FIG. 12.—PISOLITE-ROCK (Vichy).
× 9. Ordinary light.

—a double carbonate of sodium and calcium. The
dendritic tufa is the most abundant; it varies in
thickness from 20 to 50 feet over a very large area of
the shores and floor of the old lake. It often presents
remarkable dome-like and mushroom-shaped bodies,
with radiate internal structure. The deposit deter-
mines some remarkable scenery which is well figured
in Russell's work.[1]

[1] Russell, *Lake Lahontan*; see especially plates xxi. and xxii.

Oolite and Pisolite.—Under this general heading are included a number of calcareous rocks of varying origin, but all agreeing in the possession of a characteristic structure somewhat resembling the roe of a fish, or in the coarser forms a heap of peas. It appears that oolitic and pisolitic structures may originate in
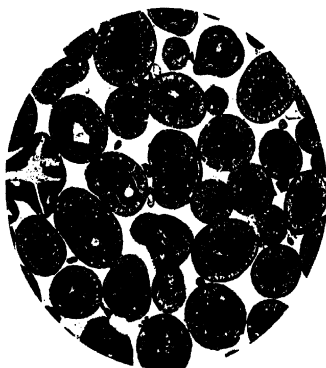
FIG. 13.—OOLITIC STRUCTURE IN LIMESTONE (Rag).
(Ketton, Rutlandshire.)

three different ways, mechanical, organic, and chemical. The mechanical and organic types are dealt with elsewhere (pp. 129 and 133). The simplest type of oolite is that in which the rock is made up of an aggregate of spherical bodies usually about 1-2 mm. or less in diameter, cemented by some interstitial material, usually calcite. When examined under the microscope it is found that two chief types of structure may be

distinguished.[1] The grains consist of minute pris-
matic crystals of aragonite or calcite which in one type
are arranged radially, and in the other tangentially;
each grain commonly consists of several layers of such
crystals, separated by concentric lines which are of
the nature of growth-zones, and indicate pauses in
deposition. Most commonly in a medial section a
nucleus of some kind can be distinguished, such as a
minute sand-grain or a chip of shell. It seems clear
that these grains have been formed by precipitation of
calcium carbonate from a saturated solution in water,
most probably while the whole mass was in a state of
gentle agitation, so that the grains could roll about
and deposition was fairly uniform on all sides; some-
times the grains are compound, possessing two or
more nuclei. This structure is found in limestones
of all ages, but is specially prominent in the Jurassic
system, which on this account was formerly known
as the Oolitic system. The oolitic limestones of the
Jurassic afford some of the most valuable building-
stones of this country, such as those of Portland and
Bath, the Ketton, Clipsham, and other stones of
Northampton and Rutland, and the Ancaster stone
of Lincolnshire.[2]

Perhaps the best known of all calcareous deposits
of purely inorganic origin are those so extensively

[1] Sorby, Pres. Add. Geol. Soc. for 1879, *Q.J.G.S.*, vol. xxxv,
1879, p. 74. Wethered, *Quart. Journ. Geol. Soc.*, vol. li, 1895,
p. 196.
[2] Watson, *British and Foreign Building Stones*, Cambridge,
1911, pp. 166-84.

represented in limestone caves. Their mode of formation is essentially the same as that just described. The water percolating through the overlying limestone becomes charged with calcium carbonate, which is deposited when the carbon dioxide is given off in contact with the air. The process is assisted by the evaporation of the water. A film of calcium carbonate forms over drops hanging from the roof, and by gradual accretion long pendent icicle-like bodies with radial or concentric structure are produced. Similarly, the drops falling on the floor build up masses, which often take the form of pillars. The pendent masses are called *stalactites*, the floor material, *stalagmites*. Deposits of this kind occur in nearly all limestone caves. British examples are found in West Yorkshire (Clapham Cave, Ingleborough, and Victoria Cave, Settle), Derbyshire, and the Mendip Hills (Cheddar Caves). All of these are in the Carboniferous limestone. Foreign examples are very numerous. The following may be specially mentioned : the caves of Han in Belgium, those of Carniola and other districts in the south-west of the Austrian Empire, the Mammoth Cave of Kentucky, and the caves in the Dolomite of the Transvaal and in the Cango series of Cape Colony.

Dolomite Deposits.—The great majority of the dolomite rocks or magnesian limestones are undoubtedly formed from limestones by a process of metasomatic replacement, and are therefore described elsewhere (see p. 214). But a few instances

have been described in which the dolomite is an original mineral formed by deposition from a saturated solution of calcium and magnesium carbonates. In these cases the deposits of dolomite are associated with rock-salt and gypsum or anhydrite, so that they were obviously formed in salt lakes or in inland seas. Cullis [1] has shown that the Trias marls of Gloucestershire and Worcestershire contain minute crystals of dolomite of very perfect rhombohedral form embedded in the marly matrix. Since these marls are known to have been formed in salt lakes, it is suggested that the dolomite crystallised from solution at the time when the marl was being deposited from suspension.

The middle Triassic strata of Thuringia and Württemberg contain important beds of dolomite, often characterised by a peculiar cellular structure (Zellendolomit). They are associated with rock-salt and gypsum or anhydrite, and are often distinctly bituminous. The general facies of the Triassic rocks of Central Europe indicates deposition in lake-basins of highly saline composition ; and it appears certain that some, at any rate, of the numerous beds of dolomite were originally deposited as such, while others indubitably result from the metasomatic alteration of limestones by saline solutions containing magnesium compounds.

[1] Cullis, " On a Peculiarity in the Mineralogical Constitution of the Keuper Marl," *Rep. Brit. Assoc.*, Leicester, 1907, p. 506. See also Wade, " Some Observations on the Eastern Desert of Egypt," *Quart. Journ. Geol. Soc.* vol. lxvii, 1911, p. 245.

A very complete chemical and mineralogical examination of the dolomites of Southern Tyrol led Professor Skeats to the conclusion that the greater part of them had been formed by a metasomatic replacement of calcium carbonate by dolomite, but in the Raibl beds he found layers of dolomite often intimately associated with gypsum in such a way as to leave little doubt that local movements of upheaval led to the enclosure of lagoons and caused concentration of sea-water, leading to deposition of the calcium as gypsum and of the magnesium as dolomite.[1]

An interesting example of a coal-seam passing laterally into a dolomite rock has been described by Strahan[2] from the Wirral Colliery in the Parkgate coalfield, Cheshire. The seam, which is normally of good quality, undergoes when followed along the workings in one direction a change of character : bands of stony material from 1 to 10 inches thick make their appearance, and these thicken out so as eventually to form the whole seam, the complete change occurring in a distance of about 250 yards. The rock has a black or grey colour, due to the presence of coaly matter ; it presents a pisolitic or botryoidal appearance, and its component grains have a radial crystalline structure. Its composition is essentially that of a dolomite, with a little carbon, iron oxide,

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[1] Skeats, " On the Chemical and Mineralogical Evidence as to the Origin of the Dolomites of Southern Tyrol," *Quart. Journ. Geol. Soc.*, vol. lxi, 1905, pp. 97-139 (see especially p. 137).

[2] Strahan, " On the Passage of a Seam of Coal into a Seam of Dolomite," *Quart. Journ. Geol. Soc.*, vol. lvii, 1901, pp. 297-306.

silica, and alumina. The deposit has evidently origin-
ated as a tufa formed in shallow water, in the presence
of some organic material, and it is possible that cal-
careous algæ took some part in the process. Its
dolomitic portion must have been formed by deposi-
tion from water saturated with the carbonates of lime
and magnesia, and there is every reason to regard
it as an original deposit rather than one formed by
the dolomitisation of a limestone.

Silica Deposits.—Silica in the form of quartz
is almost wholly insoluble in water at the normal
temperature and pressure ; but other forms of silica
are soluble to a considerable extent, especially in
the presence of alkaline carbonates. Consequently
hot springs of deep-seated origin often bring up
much dissolved silica and deposit it at the surface.
Important examples of such deposits are afforded by
the geysers of certain volcanic districts, especially
of Iceland, the Yellowstone Park, and New Zealand.
Most of the geysers of Iceland rise from basins of
sinter deposited by the water, and similar material
precipitates from the effluent streams. The details
of the process have been carefully studied by Weed [1]
in the case of the siliceous sinter of the Yellowstone
region ; he finds that the actual separation of the
solid matter is to be attributed to cooling, evapora-
tion, relief of pressure, chemical reactions between
different waters, and the action of algæ. In the latter

[1] Weed, *American Journal of Science*, vol. xxxvii, 1889, p. 351,
and *Ninth Ann. Rep. U.S. Geol. Survey*.

case the silica forms a gelatinous layer upon the algous growths and after their death hardens to sinter. One of the most famous examples of siliceous sinter were the white and pink terraces of Rotomahana in New Zealand ; but these were entirely destroyed by the eruption of Tarawera in 1886.[1]

According to Weed, siliceous water may have either an acid or an alkaline reaction. Acid waters contain free hydrochloric and sulphuric acids, and besides silica they often deposit sulphur and efflorescent alum salts. Alkaline waters usually deposit pure siliceous sinter, closely allied to opal. The hot springs of the Yellowstone Park deposit a great variety of substances, including sulphur and arsenic, while at Steamboat Springs in Nevada numerous compounds of metals are found, including sulphides of antimony, arsenic, lead, copper, and mercury, together with gold, silver, and traces of other metals.[2]

Solutions of silica percolate through the rocks of the earth's crust, and often produce a variety of chemical changes of a metasomatic nature : these may be summed up under the general heading of silicification, and are described elsewhere (see p. 207). They also play a very important part in cementation (see p. 175), but it must be remembered that there is a close analogy between this process and deposition at the surface as described in this section.

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[1] Martin, " The Terraces of Rotomahana," *Quart. Journ. Geol. Soc.*, vol. xliii, 1887, p. 165.
[2] Becker, *Mon. U.S. Geol. Survey*, vol. xiii, 1888, p. 343.

Iron Deposits.—Nearly all natural waters contain iron in solution, chiefly in the form of carbonates and salts of organic acids, more rarely as chlorides and sulphates. Vegetable and animal matter by its decomposition gives rise to carbonic acid and acids of the humic group ; these are carried through the underlying rocks by percolating water, and leach out the iron compounds contained in them. On again coming into contact with the air, the iron-bearing solutions are oxidised, and the iron precipitated in the solid form as oxide or hydroxide, forming deposits of limonite and other iron ores in springs, streams, and lakes (bog-iron ore, lake ore, etc.). To what extent this process of precipitation is purely chemical, or due to bacteria and other organisms, is still an open question.[1] However, for our present purpose the distinction is immaterial, since we are concerned with the results of the process rather than with its *modus operandi*. The chemical reaction involved in the formation of bog-iron ore may be expressed as follows : dissolved iron bicarbonate, on coming into contact with air, splits up into iron carbonate, carbon dioxide, and water, thus :

$$H_2Fe(CO_3)_2 = FeCO_3 + CO_2 + H_2O.$$

The ferrous carbonate rapidly undergoes further oxidation, forming ferric hydrate, thus :

$$2FeCO_3 + O + H_2O = Fe_2O_3 . H_2O + 2CO_2.$$
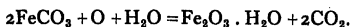
[1] Winogradsky, " Über Eisenbakterien," *Botanische Zeitung*, 1888, p. 260.

It is, however, eventually deposited in a slightly different state of hydration, as limonite, or as some other closely allied mineral.

This process is specially liable to take place in swamps and marshes, and one of the best-known examples is afforded by the lake ores of Sweden,[1] which form with great rapidity in the shallow water near the shores, where the growth of water-plants is strong and the water is but little disturbed. According to Ehrenberg the separation of the iron oxide is to be attributed to diatoms.

A very common phenomenon in marshy and peaty soils is the formation of a hard layer of iron oxide a foot or so below the surface. The formation of a *pan*, as it is called, is to be attributed to oxidation of iron-bearing solutions, which, rising from below, are brought into contact with free oxygen.

The clay ironstone and black-band ironstone, which are so abundant in the Coal Measures of this and other countries, had probably an origin similar to that of the bog and lake ores of recent formation. They consist of carbonate, oxide, or hydroxide of iron, together with proportions of silica, alumina, and carbon, which vary with the conditions under which they were formed.

[1] Sjögren, *Geol. Fören. i Stockholm Förh.*, vol. xiii, 1891, p. 373.

CHAPTER IV

ORGANIC DEPOSITS

THE third great group of sediments includes all those
deposits whose formation can be attributed directly
to the vital activity of animals or plants. Among
them are two subdivisions of pre-eminent importance
—the calcareous and the carbonaceous, together with
some others of less abundant development. The
organic deposits appertain to several different facies
of sedimentation—marine, fresh-water, and terrestrial ;
they are found in the sea, both at great and at shallow
depths, in estuaries, lakes, and rivers, also in swamps
and marshes, and even at great elevations (peat-bogs).
In fact, they are only completely absent in the most
arid desert regions, in lofty ice-covered mountains,
and in the frozen arctic lands of high northern and
southern latitudes.

Organic deposits cover a vast area of the sea-floor
at abyssal depths ; these are of a special type, and
have been treated together with the inorganic deposits
formed under similar conditions, thus avoiding needless
repetition.

Calcareous Deposits (Limestones).—This group, which is by far the largest in the whole class, is specially characteristic of the marine facies of deposit. A very large proportion of the invertebrate inhabitants of the sea possess some form of calcareous skeleton, external or internal, which may consist of either calcite or aragonite, or of both. Calcareous algæ are also frequently abundant; their importance as rock-formers has perhaps been insufficiently recognised until quite recently.[1] All these organisms obtain their supply of calcium carbonate from sea-water, into which it is brought by rivers. This, at any rate, is the principal source, although a small part of the carbonate constituent of sea-water is no doubt derived from the solution of limestone coasts and from the decay of animals and plants. The relative proportion of dissolved calcium carbonate in sea-water is very small, amounting only to about 0.012 per cent. This low content is probably to be explained by the fact that the carbonate is taken up by animals and plants almost as fast as it reaches the sea. Some of these build up solid masses of rock as a part of their life's work, as in the case of reef-corals; of others, however, only the shells and various broken fragments accumulate after the death of the organism. Similar considerations apply to fresh-water conditions, except that calcareous organisms are less abundant generally, and that reef-builders are absent.

[1] Garwood, *Geol. Mag.*, 1913, pp. 440, 490, 552; *ibid.*, 1914, p. 265; *Quart. Journ. Geol. Soc.*, vol. lxxiv, 1918, p. 1.

Fragmental Calcareous Deposits. — The simplest example of these is afforded by the coral sands and coral muds that occur in great quantity round the shores of coral islands in certain tropical and sub-tropical latitudes. Although their distribution is strictly controlled by climate, as is the case with the coral reefs themselves, they cover large areas, chiefly in the central and western Pacific. They consist essentially of comminuted fragments of coral rock broken off the reefs by the force of the waves, together with, in some cases, a varying amount of accessory mineral material, which is commonly of volcanic origin. As already stated in Chapter II (see p. 46), around certain volcanic islands in the Pacific every gradation can be traced between true coral sands and volcanic sands, and nearly all specimens contain large numbers of Foraminifera, together with shells of Heteropods, Pteropods, and other pelagic mollusca.[1] By diminution in the size of the fragments the sands grade downward into the fine-textured calcareous muds that extend far and wide over the floor of the sea, until a depth is reached at which, owing to the increased solvent action of the water and carbon dioxide under high pressure, the existence of solid calcium carbonate is no longer possible.

In regions where coral reefs do not exist, and, generally speaking, around the shores of continents

[1] Guppy, *The Solomon Islands, their Geology*, etc., London, 1887, pp. 63-85. Lister, " Notes on the Geology of the Tonga Islands," *Quart. Journ. Geol. Soc.*, vol. xlvii, 1891, pp. 602-4.

and islands, the calcareous deposits are largely composed of the remains of invertebrate animals, molluscs, brachiopods, echinoderms, corals, etc., for the most part showing signs of comminution by wave-action. Shell-banks and other accumulations of this nature are especially found on coasts that are exposed to the full force of prevalent winds; for example, they are much more abundant on the west coast of the British Isles than on the east. The floor of the shallow seas covering the continental platform of north-western Europe is very largely covered by a deposit of shell-sand, which to a great extent is composed of broken fragments of molluscan shells and other calcareous organisms; and this deposit is specially abundant in such partly enclosed areas as the English Channel and the Irish Sea.[1]

Among the older strata such deposits appear to have been abundant at many different periods, especially in Silurian, Carboniferous, and Jurassic times. They have usually been cemented to solid rocks; but an almost unconsolidated example of fairly ancient date is to be found in the Pliocene Crags of Suffolk and Norfolk, in many parts of which whole and broken shells, but little altered, are abundant.

On the shores of the Great Salt Lake, in Utah, are beds of oolitic sand, in which the grains have not yet been cemented to form a solid rock. The formation of this material is attributed by

[1] Herdman, " The Marine Zoology of the Irish Sea," *Report Brit. Assoc.*, Oxford, 1894.

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Rothpletz [1] to some organism, and in all probability some of the ancient oolitic limestones were formed in this or a similar way.

Coral Rock.—It is not proposed to discuss here the origin of coral reefs and atolls : for an account of the physical characters of these structures and of the theories that have been advanced in explanation of their origin, reference may be made to the works quoted in the footnote.[2] We are here concerned only with the lithology of coral formations. Reef-limestone differs from the majority of fragmental and organic deposits in the fact that it is largely built up in a solid coherent form from the first, and therefore constitutes a rock-mass in the strict sense, without any process of cementation. However, recent research has shown that in some cases a considerable part of the reef, especially in its lower layers, is composed of blocks of coral rock broken off from the upper portion by wave-action and piled up on the seaward slope. The seaward front of a coral reef having this structure is often extraordinarily steep, the angle sometimes being as high as 70°, and often exceeding 50°. This is explained by the fact that the angle of rest for fragmental material is much higher in water than on

[1] Rothpletz, *American Geologist*, vol. x, 1892, p. 279.

[2] Darwin, *Coral Reefs*, 3rd edit., 1889. Murray, *Proc. Roy. Soc. Edin.*, x, 1880, p. 505. Lister, *Quart. Journ. Geol. Soc.*, xlvii, 1891, p. 590. Andrews, *Monograph of Christmas Island*, 1900. " The Atoll of Funafuti," *Report of the Coral-reef Committee of the Royal Society*, London, 1904. Davis, *Science Progress*, vol. xiii, 1919, p. 420. *Bull. Geol. Soc. Amer.*, vol. xxix, 1918, p. 489. Daly, *Proc. Amer. Acad. Arts Sci.*, vol. li, p. 157.

land. In some cases the bulk of the reef probably
consists of a submarine scree, with a thin layer of
undisturbed coral rock on the top.

Typical coral rock does not consist by any means
exclusively of pure coral—there are always present
numerous shells and skeletons of marine invertebrata,
owing to the extreme abundance of life in warm
shallow seas ; furthermore, one of the most note-
worthy results of recent investigations has been the
discovery of the important part played by calcareous
algæ as reef-builders.[1] These always live in great
abundance on the outermost part of the reef, where it
is most fully exposed to wave-action. At the extreme
edge of an actively-growing reef there is generally a
slightly elevated rim, consisting very largely of calcare-
ous algæ. Pure coral is always of a very porous and
cellular nature, with many cavities occupied by the
soft parts of the animal while alive. After death the
organic part decays, and the cavities become quickly
filled by sand and mud composed of comminuted
coral rock. Siliceous and argillaceous materials are
often completely absent from coral rock ; but in some
cases volcanic material is present. According to
Professor Skeats,[2] the proportion of insoluble material
present in a limestone is to some extent an indication
of the conditions under which it was formed, even if
all structures have been destroyed by subsequent

[1] Gardiner, *Proc. Camb. Phil. Soc.*, vol. ix, 1898, p. 417.
[2] Skeats, " On the Chemical and Mineralogical Evidence as
to the Origin of the Dolomites of Southern Tyrol," *Quart. Journ.
Geol. Soc.*, lxi, 1905, pp. 97-139, especially pp. 110-11.

changes. A chemically pure limestone (*i.e.* one free from residue insoluble in acid) must have originated under the following conditions : it must have been formed rapidly, otherwise volcanic and cosmic material would certainly be present ; it must have been laid down in shallow water, since nowhere else are calcareous organisms sufficiently abundant ; it cannot have been formed near a shore-line of non-calcareous rocks. These conditions are fulfilled only in oceanic coral islands far from any other land, and in older limestones the absence of sandy or volcanic residue suggests a similar origin. Many of the raised reef-limestones of the Pacific and Indian Oceans are of remarkable purity, containing over 99 per cent of carbonates.

Nearly all recent and sub-recent coral limestones are found on analysis to contain a considerably higher proportion of magnesium carbonate than is present in the living coral. This increase is attributed to a process of dolomitisation which appears to take place almost as soon as the coral rock is formed.[1]

The group of calcareous deposits includes a number of types closely allied to coral rock in their general characters and manner of formation ; they consist, however, of organisms which are now extinct or represented only by a few rare and scattered forms. Such rocks are the Wenlock limestone, the Stromatopora limestones of the Devonian and the Crinoidal

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[1] For a full discussion of this question see the paper by Skeats already quoted.

limestones of the Lower Carboniferous strata. These have been built up partly by direct growth of the animal in place and partly by the accumulation of animal fragments. These ancient deposits are of interest to the palæontologist on account of the richness of their fauna, and the evidence that they afford as to the physical and climatic conditions of past ages. Most of them have undergone recrystallisation, and when cut and polished often form handsome ornamental building stones, generally, though incorrectly, called marbles. Of more modern character are the shell-limestones and oyster-beds of the Jurassic and the fresh-water *Paludina* limestones of the Purbeck and Wealden series, often called Purbeck and Sussex marble respectively. Some varieties of oolite and pisolite also belong here, though many of the deposits comprised under these names are clearly of chemical origin (see p. 117). Certain oolites and pisolites are formed by the accumulation of small pebbles of an older limestone, rounded by attrition, exactly as in the case of the arenaceous deposits, while others are due to the growth of peculiar organisms of rather indeterminate character, possibly algæ. Such is the origin, for example, of the so-called "Pea-grit" found in the Inferior Oolite. of the Cotswolds, in which Mr. Wethered has described the existence of interlacing tubular structures attributed to an organism which he calls *Girvanella*.[1] The typical oolitic limestones are described elsewhere under the heading of

[1] Wethered, *Quart. Journ. Geol. Soc.*, vol. li, pp. 196-206.

chemical deposits, since they have for the most part been formed by precipitation of material from solution.

It has long been recognised that calcareous algæ play a considerable part in the structure of modern coral reefs, and Prof. Garwood has recently called attention in several papers[1] to their wide-spread occurrence as constituents of some of the older limestones, especially those of Palæozoic age, in northern and western England, southern Scotland, and the Baltic region ; these organisms reached their highest development as rock-builders in the Ordovician rocks of Ayrshire (Craighead and Stinchar limestones), in the Silurian limestones of the island of Gotland in the Baltic, and in the Carboniferous limestone in Westmorland. In the Mesozoic rocks they are of less importance, but numerous examples are recorded from the Tertiary strata of the Continent ; one of the best known of these is the *Lithothamnion* limestone (*Leithakalk*) of the Vienna basin and Moravia.

Crinoidal Limestone.—The Crinoidea, a class of the phylum *Echinoderma*, are of great importance as rock-formers, and enormous masses of limestone consist to a large extent of their remains. The Carboniferous limestone is a notable example, and similar deposits are being formed at the present day in the Irish Sea. Other organic remains both of animals and plants which possess a calcareous shell or skeleton are instru-

[1] Garwood, *Rep. Brit. Assoc.*, 1913, Section C ; also *Geol. Mag.*, 1913, pp. 440, 490, 552 ; *ibid.*, 1914, p. 265 ; *Quart. Journ. Geol. Soc.*, vol. lxxiv, 1918, p. 1.

mental in building up the rocks classed as limestones, although this designation also includes rocks formed by inorganic processes both mechanical and chemical (see p. 113).

Chalk.—This is a soft white limestone, specially characteristic of the Upper Cretaceous formation, although a very similar rock occurs also in the Portland series (Upper Jurassic) of Dorsetshire. The Chalk is, as a rule, a remarkably pure limestone, often containing 97 or 98 per cent calcium carbonate, the balance being quartz and other minerals insoluble in acids.[1] This deposit is largely composed of minute shell fragments and tests of *Globigerina* and other foraminifers. These are so characteristic of the Chalk that when they were discovered to be an abundant constituent of deep-sea oozes it was at once concluded that Chalk was also an abyssal deposit. Against this view is the presence in Chalk in many places of abundant fossils of not particularly deep-water character, as well as the sand-grains before mentioned. It is now supposed that the Chalk was laid down in a partly enclosed sea, not necessarily far from land, with abundant planktonic fauna. The precipitation of the calcium carbonate may have been due to bacteria.[2] One of the most notable features of the Chalk is the presence almost everywhere of abundant

[1] Sorby, "Pres. Address," *Quart. Journ. Geol. Soc.*, vol. xxxv, 1879, p. 78. Cayeux, "Contribution à l'étude micrographique des terrains sédimentaires," *Mém. Soc. Géol. Nord*, vol. iv, 1897, and *Ann. Soc. Géol. Nord*, vol. xxvi, 1897, p. 168.

[2] Drew, *Dept. Marine Biology, Carnegie Inst.*, vol. v., 1914.

siliceous nodules and concretions known as *flint*. These are obviously of secondary formation, and due to segregation of silica originally disseminated through the rock, probably in the form of sponge-spicules. They vary much in size, form, colour, and relative abundance in the Chalk of different horizons and different districts, and there is a very close resemblance between them and many forms of chert (see p. 208).

Carbonaceous Deposits.—This group results from a special type of decomposition which under certain circumstances affects organic matter. This process differs from ordinary decomposition in the limited part played by oxidation, and the consequent abundant production of compounds belonging to the hydrocarbon group, especially members of the paraffin series, C_nH_{2n+2}, and the olefines, C_nH_{2n}. The active agents are bacteria of the anærobic type; and the formation of such carbonaceous deposits goes on most readily in situations where the material is constantly saturated with stagnant water, and the prevailing temperature is low. Such conditions are most readily attained in Arctic and cold temperate latitudes: in the tropics rapid oxidation of organic material is the rule, owing to the high temperature and the great activity of oxidising bacteria. The most important modern representatives of the group are the peat-bogs of the northern parts of Europe, Asia, and America; while under special conditions somewhat analogous accumulations may be formed in the mangrove-swamps of the tropics.

Every gradation can be traced between modern carbonaceous deposits and the coal of the older rock systems ; and for the sake of convenience the whole subject of the origin of coal will be treated here, although, strictly speaking, coal is a product of metamorphism.[1]

Tundra.—The peculiar type of deposit included under this name, which is taken from the Finnish language and is now universally adopted, is found in the coldest regions of the northern hemisphere, ranging from Finland through northern Russia and Siberia into Alaska and the great plains of Arctic America. The climatic conditions prevailing throughout this region are specially favourable to the growth and limited decay of mosses and other lowly plants, together with heaths, *Empetrum*, and the Arctic birch and willow. Since vegetable matter is a bad conductor of heat, the subsoil remains permanently frozen throughout a great portion of this region. The surface is covered with hummocky masses of living and partially decomposed vegetable matter, which in its lower layers forms great thicknesses of peaty material. The decomposition of the vegetable matter appears to be very slow, and the peat is poor in mineral matter.[2]

Upland or Hill Peat.—Peat-bogs are very common in many of the upland and mountainous regions

[1] For an admirable summary of the latest investigations on this subject, with an extensive bibliography, see Arber, *The Natural History of Coal*, Cambridge, 1911.

[2] Ramann, *Bodenkunde*, 3rd edit., Berlin, 1911, p. 578.

of the British Isles, Scandinavia, and many other temperate and sub-Arctic lands. Their distribution and character depend very largely on climate ; but this is evidently not the sole factor, since it has been shown that in the West of Scotland, which would climatically appear to be especially favourable to peat, not only is its growth at a standstill, but it is actually now being destroyed to some extent by erosion.[1]

The composition and character of upland peat show much variation : where the deposit is thick, it is often possible to trace a definite succession of alternating layers composed of different types ·of vegetation. In the peat-mosses of Scotland, Lewis has established a clear succession of bog and forest floras, divided into nine stages : the lowest of these and another, at a somewhat higher horizon, are distinctly Arctic in character; the forest beds indicate periods of milder climate, when the limit of tree-growth was at a much higher level than at present. In Scotland a birch forest and a pine forest have been determined ; in Scandinavia there are four successive forest beds, of birch, pine, oak, and spruce respectively. From these facts it is certain that the peat-mosses of Scotland and of northern England date back as far as the later stages of the Glacial period, and they indicate the existence of at least one mild inter-Glacial period, when the climate was probably somewhat warmer than it is now. The surface layers of upland

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[1] Lewis, " The Sequence of Plant Remains in the British Peat Mosses," *Science Progress*, vol. ii, 1907, p. 307.

peat consist of living plants, mosses, and roots of cotton-grass, heather, etc., and this graduates downwards into a dark brown or black, somewhat spongy material, which becomes less fibrous and more dense in its lower layers. Trunks and roots of trees when present at some depth are often converted into a substance resembling lignite.

Lowland or fen-peat differs from hill-peat chiefly in the nature of the plants of which it is composed. These usually consist largely of rushes, sedges, and other water-loving plants, while mosses are often completely absent. The resulting peat is of a more muddy nature, and generally black instead of brown. Molluscan shells and vertebrate remains are often abundant. This type is largely developed in the fens of eastern England and in the bogs of western Ireland. Bones and antlers of the extinct Irish elk are characteristic of the lower layers. Forest beds also occur in the fen-peat, no less than five having been observed near Ely. These are supposed to indicate periods of a somewhat dry climate, or possibly a slight temporary uplift of the whole region, followed by subsidence.

A comparison of the chemical characters of upland and lowland peats has recently brought to light an interesting fact. It has long been known that upland peats are of a distinctly acid character, and this is indicated in the common expression *sour* as applied to peaty soils. But, on the other hand, the fen-peats of eastern England are found to possess an alkaline

reaction. This shows that the chemical processes at work are not the same in the two cases, and the variation may possibly be attributable to the presence of different kinds of bacteria, whose vital activity gives rise to dissimilar products.

Coal.—The term coal is here used in its broadest sense to indicate the alteration products of the carbonaceous accumulations of past ages. In different parts of the world beds of coal are found in all the stratified formations from the Carboniferous to the Tertiary; and, as would naturally be expected, the older ones have undergone more change than the newer, so that the chemical and physical classification runs approximately parallel to the chronological order. In exceptional cases, however, coal deposits of later date have locally undergone a higher degree of metamorphism so as to approach closely in character to the earlier ones. Coals in general may be conveniently divided into four groups as follows : [1]

　　　　　1. Lignite and Brown coal.
　　　　　2. Humic or Bituminous coals.
　　　　　3. Sapropelic coals.
　　　　　4. Anthracitic coals.

Graphite occasionally occurs in sedimentary rocks, or in crystalline rocks derived from them, and is regarded by some authorities as the extreme product of the metamorphism of coal.

[1] Arber, *The Natural History of Coal*, 1911, pp. 13-19. See also Potonié, *Die Enstehung der Steinkohle und der Kaustobiolithe überhaupt*, 5th edit., Berlin, 1910, and Dannenberg, *Geologie der Steinkohlenlager*, Berlin, n.d., pp. 5-9.

By some writers the terms *lignite* and *brown coal* are used as synonymous, whereas others distinguish between them. It is, however, universally recognised that a transition exists, and the difference is only one of degree. A lignite may be defined as a coal of which the dominant constituent is wood, so little altered that the form and structure are evident on inspection ; associated with the wood, and with fragments of bark and leaves, is a considerable amount of structureless material. There are many varieties, some loose and fibrous, others compact and earthy.[1] Lignites are rare in Britain, the only important example being at Bovey Tracey, in Devonshire. Here thick beds of lignite are associated with deposits of china clay, etc. The whole deposit is of Oligocene and Miocene age.[2] Great deposits of lignite occur in the Cretaceous and Tertiary strata of North America and other countries.

Brown coal in the narrower sense shows little or no woody structure, and resembles a hard peat or sapropelic coal in appearance ; the colour, however, often has a brownish tint. Brown coal is unknown in Britain, but is abundant in the Tertiary beds of Germany, Russia, and Japan.

The humic or bituminous group includes the ordinary house, coking, and steam coals, of which the appearance is so familiar as scarcely to need description. As a rule they consist of a series of

[1] Arber, *op. cit.* p. 14.
[2] Reid, " The Lignite of Bovey Tracey," *Phil. Trans.*, B, vol. cci, 1910, p. 161. *Spec. Rep. Min. Res. Gt. Britain*, vol. vii, 1918, p. 2.

alternating bright and dull layers; in the latter only can remains of vegetable tissues sometimes be seen. They are generally well jointed, breaking into rectangular lumps, and the joint faces are often more or less covered with a thin layer of iron pyrites, ankerite,[1] or some other mineral. The coals of this group vary a good deal in chemical composition, so that different varieties are suitable for different purposes, for heating, steam-producing, gas-making, and the manufacture of coke.

The sapropelic coals include the varieties known as Cannel coal and Boghead coal or torbanite. These show no definite structure, and break with a conchoidal fracture. They possess a black colour and dull surface and do not soil the fingers. Boghead differs from cannel only in containing a higher proportion of ash. Cannel coal often occurs as lenticular bands in seams of humic coal, and sometimes in considerable quantity, as at Wigan in Lancashire. Boghead coal is rare in Britain, being found only in Scotland; it is more common in France and Russia, and occurs in large quantities in the Permo-Carboniferous strata of Australia and South Africa.

Anthracite differs entirely from the other coals, as it has a bright semi-metallic lustre, and conchoidal fracture is very conspicuous. It will only ignite at a high temperature, but gives off great heat, with little flame or smoke.

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[1] Crook, " On the Frequent Occurrence of Ankerite in Coal," *Min. Mag.*, vol. xvi, 1912, p. 219.

The principal constituents of all coals are carbon, hydrogen, oxygen, and nitrogen, together with a variable proportion of mineral matter known collectively as ash. The differences between the several varieties above enumerated depend on the proportions in which these constituents are present. These differences are shown in the following table : [1]

	Carbon.	Hydrogen.	Oxygen and Nitrogen.	Ash.
Moor peat . . .	53.59	6.33	27.84	12.24
Lignite. . . .	57.28	6.03	36.16	.59
Brown coal . . .	61.20	5.17	21.28	12.35
Wigan cannel . .	80.07	5.53	10.20	2.70
Newcastle humic coal.	83.47	6.68	9.59	.20
Anthracite . . .	91.44	3.36	2.79	1.52

It will be seen that the percentage of carbon increases steadily, the hydrogen remains sensibly constant, except in anthracite, the oxygen and nitrogen decrease, and the ash shows irregular variations.

Origin of Coal.—The best-known explanation of the origin of coal and one that has long held the field may be described as the "peat-to-anthracite theory." It supposes that a regular gradation can be traced between modern peat and anthracite through the various stages enumerated in order above, or, in other words, that all coals were formed by more or less complete alteration of one original peat-like substance. So far as the organic constituents are

[1] Arber, *The Natural History of Coal*, 1911, p. 9.

concerned, this theory is plausible; but if the proportion of mineral matter be taken into account, a difficulty at once arises. The supposed process may be summarised as a concentration of carbon-hydrogen compounds by elimination of oxygen and nitrogen; but by this means the ash, being non-volatile, must also be concentrated, so that anthracite should contain the highest ash-percentage. An inspection of the above table shows that this is by no means the case: anthracite contains less ash than cannel, and much less than peat. Lignite, brown coal, and boghead also show abnormalities in this respect. The figures given above clearly show that the varieties of coal must have originated from widely differing substances. Further, there is no proof that the carbonaceous accumulations of the earlier periods had, when newly formed, a composition similar to that of recent peats; it is certain that they consisted of quite different plants, the nature of which is mostly still unknown.

The balance of present opinion inclines to the view that lignite and brown coal were probably formed in a manner analogous to that of some recent peats, of lowland or fen type rather than upland, perhaps very similar to the forest beds in our older peats. But the remaining varieties must have had a different origin.

It is impossible here to set out in detail all the arguments that have been brought forward in support of the different views as to the origin of coal and

the manner of its accumulation. One thing at any rate is clear : coal has been formed in several different ways, from material which originally showed widely varying characters. Recent research has shown that many coal-seams have been formed in lakes, deltas, estuaries, and lagoons, both in fresh and in brackish water. These must necessarily consist to a large extent of drifted material, though the vegetation growing outwards from the shore doubtless also played a con-siderable part. A well-known instance of accumula-tion in fresh-water lakes is afforded by the coal-basins of St. Étienne and Commentry, in central France. These are the delta - deposits of torrential streams, often containing large masses of wood and roots of trees.[1] A careful investigation of the constituents of humic coals, so far as they are determinable, has shown that the plant-remains are almost always in a frag-mentary condition ; and it is believed that in all cases they have drifted in water for an appreciable, though perhaps not a great, distance. The general character of the seams themselves and of the associated sediments suggests accumulation in gently-moving water either in the estuaries of rivers or in coastal swamps, which must have closely resembled the mangrove swamps of tropical coasts. In some instances also coal-seams are . closely associated with beds containing marine fossils ; such seams must have been formed in estuaries or shore lagoons, or even in the sea. The character

[1] Grand'Eury, " Mémoire sur la formation de la houille," *Ann. des Mines*, Mém., Sér. 8, vol. i, 1882, p. 99.

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of the Coal-measure strata in general, with their alternations of comparatively thin beds of coal, shale, and sandstone, is most easily explicable on the supposition of a considerable area of nearly level land in a region of unstable equilibrium, which was constantly undergoing elevation and depression within a small vertical range, the general downward movement preponderating. As the land sank, the swamps and lagoons encroached on the forests and killed off the vegetation ; and this, decaying in the water, formed a carbonaceous accumulation, assisted by the growth of water-loving plants. Further submergence led to the formation of sands and shales, with occasional masses of drifted vegetation, giving rise to the coaly streaks that are so common in these strata. Then elevation restored the land-surface and led to renewed growth of the purely terrestrial vegetation, and so the process was repeated many times.

In some cases, however, the coal was probably formed from material that actually grew on the spot where it is now found. The growth-in-place theory is based on the existence of underclays or seat-earths below many coal-seams. However, it is by no means clear that underclays are always old soils, in spite of the presence of roots. They vary very greatly in composition, some being highly siliceous, while others are hardened carbonaceous oozes that may have been lake or lagoon deposits. Coal-seams are known to rest directly, without the intervention of an underclay, on sediments of all kinds, even on glacial con-

glomerates, as at Vereeniging in the Transvaal. The very perfect preservation of plant-remains on the upper surfaces of some coal-seams is also adduced as an argument in favour of the growth-in-place theory, since vegetable structures are soon destroyed by water-transport.

The controversy between the supporters of the " drift " and the " growth-in-place " theories is now mainly of historic interest, since it is clear that both of these theories are applicable in different instances. At the present day the chief subject of argument is as to whether all varieties of coal have had a common origin. The upholders of the " peat-to-anthracite " theory are perhaps now the more numerous, but there can be little doubt that the view that supports the heterogeneous origin of the different varieties will ultimately prevail.[1]

Origin of Sapropelic Coals.—It has been shown by Renault[2] and others that boghead coal is largely made up of gelatinous algæ of very small size. These are not distinguishable in cannel coal; but transitional forms exist, so that cannel may in reality contain similar material in a more highly altered state. It was recognised long ago that one of the principal constituents of some varieties of cannel coal is the spores of lycopods, while the rest of the material was

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[1] Arber, *The Natural History of Coal*, 1911, chapters iv and v.

[2] Renault, *Sur quelques micro-organismes de combustibles fossiles*, St. Étienne, 1900.

probably once a carbonaceous slime. ·Potonié [1] has applied the term *sapropel* to organic gelatinous matter of this kind, formed by decomposition in stagnant water, in marshes or in lakes, and even on the shores of salt-water lagoons. It is now generally believed that cannel and boghead coals have been formed in this way. The abundance of spores is thus easily explicable, since they are readily transported by wind; while the rest of the material may be largely plank-tonic in origin, and consist of the remains of floating organisms of all kinds, both animal and vegetable.

A large amount of attention has been devoted to the origin of anthracite, and many writers have re-ferred the peculiar characters of this substance to some kind of metamorphism of humic coals. However, a detailed study of the anthracite region of South Wales [2] has shown that here, as in other cases, the materials that gave rise to humic and anthracitic coals were of diverse character. The nature of the original substance of anthracite is still obscure, and it may constitute a third type, differing from both the humic and sapropelic coals. The most noteworthy feature of the anthracitic coals is the extremely low proportion of ash (see table, p. 143), and this fact seems to point to deposition of extremely pure carbonaceous material in water. What the origin of this material may have been it is impossible as yet to say.

[1] Potonié, *Die Entstehung der Steinkohle*, 5th edition, Berlin, 1910, p. 19.

[2] Strahan and Pollard, " The Coals of South Wales," *Mem. Geol. Survey*, 1908, chap. ix.

Jet is a highly-bituminous black substance, closely allied to the sapropelic coals and to anthracite; it is very compact in texture, and is capable of taking a high polish. It is abundant in one division of the Upper Lias of the Yorkshire coast [1] and in Württemberg.[2] It has been formed by the alteration of fossil drift-wood, or possibly in some cases by a segregation of bituminous matter in the rock.

Siliceous Organic Deposits. — Although of considerable interest, these are not found in great quantity. Most of them are composed of the skeletons of Radiolaria or of Diatoms. Both groups of organisms are very widely distributed, though the individuals are of very small size, and it is only under special circumstances that their remains give rise to accumulations of any importance. Both Radiolaria and Diatoms form deposits on the floor of the sea at great depths : these are described elsewhere (see p. 86). Radiolaria are likewise present in considerable numbers in many marine deposits of ancient date, as, for example, in the Chalk. One of the most notable instances of the abundant presence of this division of the Protozoa is afforded by the so - called Radiolarian earths of Barbados, in which certain beds consist very largely of their siliceous skeletons. Associated with the Radiolarian deposits are beds very similar to the Globigerine Ooze and Red Clay of recent abyssal

[1] Fox-Strangways, " The Jurassic Rocks of Britain," vol. i, Yorkshire, *Mem. Geol. Survey*, 1892, p. 455.

[2] Potonié, *Die Entstehung der Steinkohle*, 1910, pp. 78-81.

deposits. From their general character it is concluded that the so-called oceanic deposits of Barbados, which are probably of Pliocene age, were laid down in deep water in a region that has subsequently undergone a great uplift.

Diatom-earth, Tripoli-powder, and Kieselguhr are names applied to accumulations of diatoms formed under terrestrial conditions, in lakes and swamps. Kieselguhr is a white or yellowish chalk-like mass, which often contains plant-remains and is generally found in association with peat, as, for example, in Skye and the North of Ireland, and in the Oligocene Brown Coal formation of Germany. In America beds of Kieselguhr more than 300 feet thick are found in Oregon, Nevada, and California. This substance is now of considerable commercial importance. It is sometimes employed for polishing purposes ; but its chief technical application is as an absorbent in the manufacture of high explosives.

It has already been pointed out that the separation of silica from the waters of many hot springs is due to the vital activity of algæ. These plants deposit the material in their own tissues as a siliceous jelly, which hardens to sinter after the death of the organisms (see p. 122). Hence siliceous sinter formed in this way is strictly of organic origin, but as a matter of convenience it is here placed with the chemical deposits..

Besides the cases enumerated above, fragments of siliceous organisms play a considerable part in

building up many sedimentary deposits. Perhaps the most important of these are sponge-spicules, which occur in great abundance in both modern and ancient sediments, and especially in the Cretaceous system (see p. 79).

PART II

THE METAMORPHIC DERIVATIVES OF THE SEDIMENTS

CHAPTER I

METAMORPHISM IN GENERAL

Meaning of the Term.—The term " metamorphic " was applied by Lyell in 1833 [1] to the crystalline schists and slates, which he considered to have been originally deposited in the form of sediment, and to have obtained their crystalline texture subsequently through the combined agency of heat and water. Since the time of Lyell it has been shown that the crystalline schists are not all, as he thought, altered sediments, but that many of them are rocks of igneous origin which, during or since their consolidation from a molten magma, have had impressed on them a banded and foliated character by internal differential movements under the influence of pressure or mechanical stress.

The most modern writers on the subject (*e.g.* Van Hise) [2] use the term metamorphism in its widest possible sense, viz. to connote any change in the

[1] *Principles of Geology*, 1st edition, published in 1833 ; from " meta," implying change, and " morphe," form.

[2] Van Hise, " A Treatise on Metamorphism," Monogr. xlvii, *U.S. Geol. Surv.*, 1904, p. 38.

constitution of any kind of rock, through whatever agency. In this sense the chemical changes embraced by the terms " cementation " and " weathering " must also be included under the head of metamorphism. Thus the formation of a sandstone by the deposition of a siliceous cement between the particles of a loosely aggregated quartz-sand is considered by this school to be as much a metamorphic process as the formation by hydrothermal agencies of a quartzite, of which the component quartz grains are in actual (sutured) contact. Similarly, the breaking down by weathering of these rocks to a loose aggregate of sand is equally a metamorphic process, but of the reverse order.

Geology teaches us that the conditions under which a rock exists as a constituent of the earth's crust are perpetually changing. The conditions of low temperature and low pressure, existing at or near the surface, may be exchanged for those of high temperature and pressure existing at great depths, the agents whereby these changes of physical condition are produced being the removal of material by erosion, its accumulation by sedimentation, crustal movements, igneous intrusion, etc. Logically, metamorphism may be regarded as the sum-total of the modifications undergone by a rock under the influence of the forces of gravity, heat, and chemical energy, the agents through which these forces act being gases, liquids (mainly water), and organisms (*e.g.* bacteria).

An important principle underlying metamorphism

is that the rocks are always modified in the direction of an adjustment to new conditions. Each component mineral is stable only within certain limits of temperature and pressure. If these limits are overstepped, a molecular rearrangement takes place and new minerals are formed that are relatively more stable under the new conditions than those which they replace. There is in this respect a great difference in minerals. Some, like leucite and olivine, are, under new conditions, especially prone to give rise to new minerals ; while others, like quartz and zircon, are remarkably persistent throughout a great range of temperature and pressure.

It is evident that during its life a rock may undergo many distinct kinds of metamorphism, according to the different positions in the earth's crust in which it successively finds itself. Thus at or near the actual surface it will be subject to the destructive forces of weathering (*the zone of katamorphism* of Van Hise). Below the permanent water level it will undergo cementation or metasomatism by the introduction of fresh mineral matter, in addition to, or in exchange for, a previous constituent. Buried still lower, it will come within the range of high temperature and high pressure (*the zone of anamorphism* of Van Hise), and may undergo complete recrystallisation. These various changes together constitute what is termed *the metamorphic cycle*. Since the cycle, whether complete or not, may be repeated any number of times, it is evident that the changes to which rocks are liable, both in

structure and mineral composition, may be very complex ; in fact, so great may be the ultimate metamorphism of a rock that it is sometimes impossible to trace back its history far enough to decide whether, in the first instance, it consolidated from an igneous magma or was deposited as a sediment.[1]

Kinds of Metamorphism.— We have said above that the forces giving rise to the metamorphism of rocks are gravity, heat, and chemical energy.   Gravity is the prime cause of the crustal movements—both vertical and horizontal—that are instrumental in mountain - building ; and it is also responsible for the flow of water on the surface of the earth and for its circulation underground.   The modification of rocks that arises directly from motion has been characterised in geological literature as *mechanical* or *dynamic metamorphism*, while those in which chemical energy and heat play the predominant rôle have been termed respectively *chemical* and *thermal metamorphism*.   There are obvious objections to this terminology, since the different forms of energy are interchangeable and no metamorphism can be ascribed solely to any one form.   Another classification of metamorphism very frequently used is by reference to the agents through which the changes are effected. Thus in *hydro-metamorphism* the prime agent is water, while *pneumatolysis* or *pneumatolytic metamorphism*

[1] For a discussion of the general principles of metamorphism see Harker, " Pres. Address," *Proc. Geol. Soc. London*, vol. lxxiv, 1919, p. lxiii.

refers to the agency of gases. None of these classifications being entirely satisfactory, we propose to found our treatment of the subject on a geological basis. Thus we shall deal with those changes that arise as a direct consequence of the intrusion of large masses of igneous rock at a high temperature under the head of CONTACT METAMORPHISM ; while those widespread changes that are produced by the deep burying of a mass of sediments in regions of high temperature and high pressure, or by the mechanical processes of folding, shearing, and kneading to which rock masses are subjected in an area of mountain-building, we shall treat of under the head of REGIONAL META-MORPHISM. On the other hand, we shall deal with the changes produced below the ground-water level under the head of CEMENTATION and METASOMATISM, and with the alterations produced in the superficial portion of the crust by atmospheric agencies under the head of WEATHERING.

Factors influencing Metamorphism.—The liability to alteration of a rock depends on its composition and on its physical character. The extent to which it is composed of minerals that are permanent under a wide range of physical conditions determines largely its capacity for resistance to attack ; while porosity and planes of separation (bedding, cleavage, joints, and faults), inasmuch as they regulate the circulation of the gases and waters that are the principal agents of change, constitute the lines of communication through which the attack can be delivered and maintained.

Climate also is of great importance : the weathering
of rocks is more rapid in tropical than in temperate
or arctic regions ; it is especially rapid in those
districts where there are great diurnal variations in
temperature ; it is more rapid in humid than in arid
regions, etc.   Position also has an important bearing :
rocks exposed to prevalent rain-bearing winds are
often more rapidly affected than those that are in
shelter.   The character of the topography, the angle
of slope, the dip of the beds, the coarseness or fineness
of the material composing them—all these conditions
have a direct influence on the rate of change.   But
of all factors influencing metamorphism, *time* is
perhaps the most potent : the longer the exposure to
a certain combination of conditions, the greater will
be the resulting metamorphism ; and it is generally
true that, *caeteris paribus*, the older the strata the
greater the alteration.   It is clear, however, that in
those regions where the conditions have not been
favourable to metamorphism, very ancient sedimentary
accumulations may have remained comparatively un-
altered.   Thus Silurian, Devonian, and Carboniferous
rocks in northern Russia have remained undisturbed
since their first deposition and are only partially
consolidated, so that rocks whose geological equiva-
lents in Britain are slates and marbles appear there as
soft blue clays and friable limestones.[1]   On the other
hand, in regions that have come within the focus of
great crustal disturbances, or have been invaded by

[1] See Geikie's *Life of Murchison*, vol. i, p. 301.

igneous intrusions, strata of comparatively recent
origin may have been profoundly modified.

Zonal Divisions of the Lithosphere.—Van Hise
divides the upper portion of the lithosphere into
(1) *a zone of weathering (katamorphism or destructive
metamorphism)* ; (2) *a zone of cementation or of meta-
somatism*; the boundary between the two being the
permanent level of the ground water, or, in other
words, the level at which the rocks are permanently
saturated. It is the level of the lowest drainage exit.

The zone of weathering is coincident with the
vadose region of Pošepný.[1] In this region there is
a free circulation of waters charged with oxygen and
carbon dioxide. The complex results of the action
of these waters are disintegration (loss of cohesion),
decomposition, and solution : in fine, a breaking down
or destruction of the rocks and a removal of their
soluble constituents. The chief chemical processes
involved are hydration, oxidation, and carbonation, a
characteristic reaction being the breaking down of the
silicates and the removal of their alkalies and alkaline
earths in solution as carbonates, while silica is set free.
Of the silica thus liberated a portion is left behind
as quartz, and the remainder goes into solution as
colloidal silica. Where sulphides (such as pyrites)
are present, the oxidation of the sulphur leads to
the formation of sulphuric acid and sulphates. As
a final result, a few simple, relatively insoluble and

[1] Pošepný, *The Genesis of Ore-deposits*, 1902, p. 18 (reprinted
from the *Trans. Amer. Inst. Min. Engs.*, vol. xxiii).

resistant minerals remain, such as quartz, hydrated oxides of iron and aluminium (limonite and bauxite), hydrated oxides of manganese (wad and psilomelane). The soluble compounds are either carried away to the sea by the overground water circulation, or transferred to the deeper-lying zone of cementation by the underground waters.

The zone of cementation is permanently saturated with water solutions. In this zone oxidation is limited to a small upper portion in which the vadose waters, coming from the zone of weathering above, rapidly part with their free oxygen. As a whole, the deep-water circulation is lacking in free oxygen and contains reducing agents. Although the deep waters are not wholly of meteoric origin, a large proportion of the cementing material is derived from the belt of weathering (silica, carbonates of calcium and magnesium, etc.). The remainder is contributed by the high-temperature magmatic waters derived from igneous emissions.[1] Thus the open spaces of rocks which, whether present as original interstices or as rents or fissures produced by orogenic forces, become gradually filled by mineral matter, and are finally completely closed. Besides the filling of openings, or cementation, metasomatic replacement of original constituents also takes place, this being, as will be seen later, especially characteristic of the carbonate rocks.

The zone of cementation may be said to be dis-

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[1] The "juvenile waters" of Suess. Cf. footnote on p. 173.

tinguished by the reverse of the processes that prevail in the zone of weathering, namely, by the deposition of mineral matter and the induration or increase in coherency of the rocks. Besides the difference in hardness there is frequently a marked contrast in colour between the two zones, the rocks of the weathered zone being deeply stained red or yellow by hydrated oxides of iron, while the unoxidised rocks below the ground water level usually present a bluish or a greenish hue, due to the prevalence of iron sulphides and ferrous silicates. The boundary between the two is often clearly demarcated by this change of colour.

The zone of cementation is succeeded downward by a region of high temperature and high pressure in which the metamorphism is regional. The depth at which this region (the *zone of anamorphism* of Van Hise) [1] is reached depends on whether the geological conditions are quiescent or are those of orogenic movement. The chemical reactions that take place in this zone are controlled both by high temperature and by high pressure, but the latter has the dominating influence. [2]

Besides hydrostatic pressure, we have also to consider " stress," or one-sided pressure, with con-

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[1] Van Hise, *loc. cit.*, p. 155.
[2] The increase of pressure with increased depth, in the case of a rock having the density of 2.6, would be as follows :

Depth in metres	10	100	1,000	10,000	20,000	40,000
Pressure in kilos per sq. cm.	2·6	26	260	2,600	5,200	10,400

sequent yielding of the rocks in the direction of least resistance. Here mechanical energy is the chief factor of metamorphism. As a result, two classes of phenomena are produced :

(1) Dislocation, or differential mass - movement (faults, thrusts, etc.).

(2) Mechanical deformation without discontinuity, or differential molecular movement.

As already stated, heat plays a part secondary to pressure in the zone of anamorphism ; it is, however, of considerable importance in promoting chemical reaction. In the absence of orogenic movement the heat is derived partly by conduction from the interior of the earth, partly from the circulation of highly-heated juvenile waters given off during the consolidation of igneous magmas. But in regions of mountain-building the heat generated mechanically during the crushing of the rock masses is of greater importance.

The high temperature and high pressure existing in this zone induce great chemical activity which, acting through the medium of aqueous solutions on the mechanically-deformed and crushed minerals of the deeply-buried sediments, is responsible for their rapid solution and recrystallisation, the new forms being more stable, more complex, and of higher density. The characteristic chemical reactions of regional metamorphism are *deoxidation, dehydration,* and *silication* (formation of silicates). Thus ferric

iron is reduced to the ferrous form, sulphates to sulphides, etc. Limonite by dehydration gives rise to hæmatite, and biotite is formed in preference to the chlorite characteristic of the zone of weathering. By silication is meant the formation of silicates by the union of silica with bases such as lime, magnesia, etc. This is especially manifested in the phenomenon known as dedolomitisation, in which the carbon dioxide of the carbonates of magnesium and calcium is replaced by silica, the minerals dolomite and calcite giving place to forsterite, olivine, diopside, wollastonite, etc. Already in the middle of last century Bischof[1] had proved by experiment that carbonates of calcium and magnesium are decomposed by silica at a boiling temperature, and subsequent researches on dedolomitisation have shown that this phenomenon takes place on a most extensive scale.

Lastly, in contact metamorphism the dominant factor is heat which, in part, is derived directly by conduction from the intrusive mass. A part, however, owes its origin to the gases and vapours given off from the cooling magma during the first stage of its consolidation, and yet another part to the circulation of the heated waters produced in the later stages of consolidation. There is, further, the direct chemical action of the gases on the sediments of the metamorphic aureole, for which the term *pneumatolysis* has been invented, and the widespread and far-reaching phenomenon of

[1] Bischof, *Lehrbuch der chemischen und physikalischen Geologie*, Bonn, 1847, vol. i, p. 349.

lit-par-lit intrusion, by which is meant the injection of a portion of the magma residuum of the intrusion between the bedding planes of the sediments.

   The Relation of the Fragmental Sediments to their Metamorphic Derivatives.—If we divide the fragmental sediments into classes according to size of constituent, the relation of the different classes to their chief metamorphic derivatives may be shown by the scheme on p. 167.

SCHEME OF SEDIMENTS AND THEIR DERIVATIVES

Size of Constituent.	Incoherent.	Cemented.	Cleaved or Foliated.
Below 0.005 mm.	{ MUD } { DUST } → CLAY (plastic) →	{ MUDSTONE } { SHALE (laminated) }	{ SLATE (cleaved). } { PHYLLITE and SCHIST (foliated). }
0.005–0.05 mm	SILT →		
0.05–2.5 mm	SAND →	SANDSTONE → QUARTZITE → { FELSPATHIC } → { ARKOSE, } { SANDSTONE } { GREYWACKE }	→ QUARTZ-SCHIST. → PARA-GNEISS
2.5–100 mm.	GRAVEL →	{ GRIT (pebbles } → { PEBBLY } { and sand) } { QUARTZITE }	→ PEBBLY QUARTZ-SCHIST.
		CONGLOMERATE (rounded fragments)	{ SCHISTOSE CONGLOMER- ATE. } { CONGLOMERATE-GNEISS. }
Above 100 mm.	{ BOULDER-DEPOSITS } { SCREE-DEPOSITS }	BRECCIA (angular frag- ments)	

CHAPTER II

CEMENTATION AND METASOMATISM

The Zone of Cementation.—This is the name given
by Van Hise [1] to that section of the earth's crust
which immediately underlies the zone of weather-
ing, the bounding plane of the two zones being the
permanent water level or "water table." In this
zone all openings, such as pore spaces, and those of
joints, faults, partings, cleavage, and bedding, are,
until closed by the deposition of mineral matter, filled
with water in circulation. The bottom limit of the
zone is coincident with the upper limit of what Van
Hise has called the zone of flow, this term being used
to indicate the fact that at these depths the pressure is
sufficiently great to produce a differential movement of
the rock particles, and thus to close all openings by
" rock-flow." [2]

The openings in the zone of cementation vary in

[1] " A Treatise on Metamorphism," *Monograph U.S. Geol.
Survey*, Washington, 1904, p. 162.

[2] Van Hise estimates that the upper surface of the zone of flow
occurs at 10,350 metres or 6.4 miles. A recent investigation by
F. D. Adams indicates, however, that small cavities may remain
open to a depth of at least eleven miles.—*Journ. of Geol.*, vol. xx,
1912, p. 97.

size from the minute pores that exist between the
constituent minerals of the rock, to the great solution-
caves of limestones. The porosity (this term being
used to express the percentage of open spaces as
compared to the volume of the rock) varies from zero
to as much as 30 per cent. It is greatest in coarse
mechanical sediments such as sandstones [1] or con-
glomerates that have not been cemented, or in recently
deposited volcanic ashes and breccias. Buckley found
that the pore spaces in some of the Wisconsin sand-
stones amounted to nearly 28·per cent. of the volume
of the rock. Mechanical deformation in a region of
mountain-building gives rise to fracturing, fissuring,
brecciation, jointing, and other planes of discission [2]
which may temporarily largely increase the open
spaces in rocks. All such openings, whether pores or
fissures, are channels for the circulation of the ground
water. But it is important to note that the size of
the passages diminishes in proportion to the progress
of cementation. Consequently circulation is at its
greatest in newly-formed sediments or in rocks that
have recently undergone fracturing. It is, on the
other hand, at its minimum in regions undisturbed by
orogenic movements, where the rocks, having been
long exposed to cementation, have had their pore
spaces and other openings completely closed ; and
this affords an explanation of the fact, often noted,

[1] Buckley, *On the Building and Ornamental Stones of Wisconsin*,
1898, p. 403.
[2] Pošepný, *The Genesis of Ore Deposits*, 1902, p. 13.

that many deep mines are dry, although as shallow mines they had been wet.

The process of cementation consists in the deposition of mineral matter carried in solution by the circulating water. When this water is of meteoric origin, its mineral burden is in the main derived from the zone of weathering; but when the water is of magmatic origin, *i.e.* is derived from igneous emissions, its mineral content must also be largely derived from the same source.

The filling of the open spaces in rocks produces veins and other masses of mineral matter. The formation of tabular and massive accumulations of mineral matter which, when they contain valuable compounds of the metals, constitute *ore-bodies*, is therefore one of the functions of cementation. But we are more concerned here with that function of cementation which consists in the deposition of mineral matter in the *pores* of the rocks.

Actual cementation is no doubt preceded in most cases by a mechanical consolidation of the loosely-aggregated fragments of a sediment, as a direct consequence of the pressure of the superincumbent rock. During this process a large proportion of the water separating the constituent particles of a rock is eliminated: in fact, it is even conceivable that muds and silts may (without any actual cementation) acquire a considerable degree of coherence merely by the squeezing out of the water and the orientation and close approximation of the mineral particles until they are only

separated by thin films of water, which then holds them together by surface tension, as in clays. Possibly there may even be a kind of welding[1] due to inter-molecular attraction, as in shales, in which cementa-tion plays only a subordinate rôle.

The filling of the interstices of rocks by cementa-tion takes place either by the enlargement of already existing mineral particles, or by the deposition of independent interstitial material. In the former case the new material attaches itself to already existing fragments of the same material, and the new and the old are in optical continuity. The cementation of sandstones by the growth of newly-deposited quartz on the old quartz grains is a familiar instance of this process of enlargement. Similar enlargements have been observed—but less commonly—in the case of other minerals, such as felspar, hornblende, augite, biotite, calcite, garnet, and tourmaline.[2] The process of cementation by enlargement is brought to an end by the interlocking of the minerals.

The following substances are important as cement-ing materials : *silica*, usually deposited as quartz, but occasionally also as opal or chalcedony ; *iron oxides*, namely, hæmatite and limonite, where there is excess of oxygen, or magnetite, where there is a deficiency of oxygen ; the *carbonates of calcium, barium, magnesium, and iron*, namely, as calcite, witherite,

[1] Van Hise, *A Treatise on Metamorphism*, 1904, p. 596.
[2] *Ibid.*, pp. 619, 626. See also *Bull. U.S. Geol. Survey*, No. 8, 1884, pp. 44-47, and *Amer. Journ. Sci.*, 1885, pp. 23-25.

dolomite, chalybite, and ankerite ; *sulphides of iron*, chiefly as pyrites, but also as marcasite, pyrrhotite, and the arseno-sulphide, mispickel ; *hydrated silicates*, such as zeolites, chlorites, epidote, serpentine, and talc ; *anhydrous silicates*, such as felspar, hornblende, and mica ; the *oxides of aluminium*, such as gibbsite and

FIG. 14.—QUARTZITE (Lower Greensand, Ightham, Kent).

Quartz grains, cemented by granular silica.
Crossed nicols.   × 13.

diaspore ; *sulphates*, such as those of calcium (gypsum) and barium (barytes) ; and *phosphates*, as in the phosphatisation of certain calcareous and argillaceous sediments.

Very frequently the cementing substance is similar to the chief mineral composing the cemented rock ; thus sandstones are most frequently cemented by quartz, and limestones by calcite.   This principle, how-

ever, is not universally true, since examples are known
of sandstones cemented by calcite (Fig. 22) and of
limestones cemented by silica. The dominant process
of cementation is undoubtedly that of silicification;
but the deposition of carbonates, sulphates, silicates,
and iron oxides plays a very important part.

As already pointed out, a large proportion of the
cementing material is derived from the belt of weather-
ing by the agency of meteoric waters, which carry down
its soluble products to the zone of cementation; but
the contribution of mineral matter by the " juvenile " [1]
waters is considerable. Further, there is the mineral
matter that goes into solution within the belt of
cementation itself as a result of chemical reactions,
such as those of metasomatic replacement.

**Factors governing Cementation and Metaso-
matism.**—There are several causes governing the
precipitation of mineral matter in the zone of cementa-
tion; they may be enumerated as follows: (1) *the
mingling of solutions from different sources;* (2) *chemical
reaction between the solutions and the rocks they traverse;*
(3) *decrease in temperature;* and (4) *decrease in pressure.*

The part played by these four factors may be
illustrated by a few examples. The first presents
little difficulty, and a single example will suffice: if
a solution containing oxygen meets one in which
iron is the chief base, hæmatite or limonite will be

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[1] Suess's term for the water (or water-gas) given off during
the consolidation of igneous magma. See *Das Antlitz der Erde,*
vol. iii, p. 630.

precipitated. The influence of the rocks traversed is, perhaps, the most important of the factors dominating cementation. It will be shown later that the process of metasomatism, or replacement of minerals by fresh matter molecule by molecule, takes place on the very largest scale within the zone of cementation. But one of the chief of these processes, and the one that will serve best as an illustration, is that of hydration, by which the anhydrous minerals are replaced by hydrated compounds, as, for instance, anhydrite by gypsum, hæmatite by limonite, and felspar by zeolites. Hydration is accompanied by expansion, the increase in volume in such cases being at least 25 per cent.,[1] so that alteration by hydration and the deposition of the new minerals thus produced are alone sufficient to account for a complete filling of the pore spaces of rocks. Mass-action is another example of the influence of the rocks traversed; and an explanation is thus afforded of the silicification which plays such an important rôle in the cementation of the sandstones. It will be seen later (Chap. V) that in the belt of weathering the carbonation of the silicates sets free a vast amount of colloidal silicic acid, and that this goes into solution and is carried by the descending waters to the belt of cementation. Colloidal silicic acid is an unstable compound, and tends to break up into silica and water. This reaction is especially promoted during

[1] The hydration of anhydrite to gypsum involves an increase of 33 per cent. in volume, which explains the contorted character of beds of gypsum originating in this manner.

the passage of the solutions through sandstones by
the fact that the already existing quartz, which makes
up the bulk of a sandstone, favours the precipitation
of fresh silica in that form. Since a high temperature
is certainly not unfavourable, and is even perhaps
favourable to the dehydration of silicic acid, the
cementation of sandstones by quartz may take place
in the lowest zones in which any water circulation is
possible.

With regard to the temperature and pressure
factors, these are of special importance in regard to
solutions ascending from zones of high temperature
and high pressure to zones of lower temperature and
lower pressure. But, as we have just seen, there are
some cases in which precipitation may be rather in-
creased than diminished by a rise in temperature.

Cementing Materials : Silica.—As already stated,
the most frequent cement of the sandstones is silica ;
and in the great majority of cases it is in the form of
quartz, often deposited in crystalline continuity with
pre-existing quartz grains. In rare instances only
does the siliceous cement consist of amorphous silica,
as in a sandstone from Paraguay, of which a micro-
scopic examination showed that the sand grains were
cemented by opal [1] (see also p. 171).

The first work on the siliceous cements of sand-
stones was done by Sorby.[2] He showed that the
so-called crystallised sandstone of Penrith (of New

[1] Pöhlmann, *N. Jahrb. für Min.*, 1886, p. 246.
[2] "Presidential Address," *Proc. Geol. Soc.*, 1880, p. 63.

Red age), in which the quartz grains frequently show perfect crystal boundaries, has been formed by a deposition of secondary quartz around an original nucleus of rounded sand grains, the crystalline continuity of the new and old quartz being demonstrated by their simultaneous extinction when a thin section is rotated between crossed nicols (see Figs. 15 and 16).

FIG. 15.—QUARTZITE (Loch Maree, Sutherland).

Between crossed nicols.   Cementation of quartz grains by enlargement.   × 15.

Such crystallised sands may be met with in deposits of various age from the Jurassic down to the Old Red, and many examples have been described by J. A. Phillips.[1]   They are especially common among the Carboniferous, Permian, and Triassic sandstones.

[1] Phillips, "On the Constitution and History of Grits and Sandstones," *Quart. Journ. Geol. Soc.*, vol. xxxvii, 1881, p. 6.

Thus the Bunter sandstones of Lancashire and Cheshire, which consist of well - rounded quartz grains formed by wind action (the so-called *millet-seed sand*), show a secondary quartz growth in crystalline continuity round original grains coated with hydrated ferric oxide. In some cases it is even possible to separate the secondary from the original
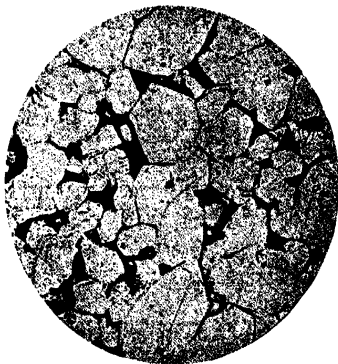
FIG. 16.—QUARTZITE, so-called CRYSTALLISED SANDSTONE
(Arlington, Columbia County, Wisconsin, U.S.A.).

An example of cementation by " enlargement," with assumption
of crystal faces. In ordinary light. (After Van Hise.)

quartz by dissolving the iron coating with hydrochloric acid.

Where the cementation has been continued sufficiently long, the cemented grains fit so closely together that they mutually interfere to prevent the development of crystal faces, as in the ganister of the South

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Yorkshire coal-field. The Stiper Stones quartzite near Shrewsbury (of Ordovician age) is another good example of the enlargement of sand grains by secondary growth of silica without the development of crystal faces. Here the dividing line between secondary and original quartz is well marked, on account of the original sand grains being rather cloudy, whereas the

FIG. 17.—QUARTZITE (Maughold, Isle of Man).

Quartz grains, cemented by granular quartz.
Crossed nicols.   × 20.

secondary quartz, which is in optical continuity with the sand grains, is distinguished from them by its pellucidity. A similar rock occurs in the Lickey Hills of Worcestershire.

Many sandstones are cemented partly by quartz and partly by the complex mixture of finely-divided materials that constitute clay (see p. 200). Although

this clayey cement cannot as a rule be resolved under the microscope, minute flakes and particles of mica (sericite), chlorite, epidote, calcite, and needles of rutile can occasionally be made out. Of the many sandstones with mixed siliceous and clayey cements, the Mayhill sandstone, described by J. A. Phillips,[1] may be taken as a type.
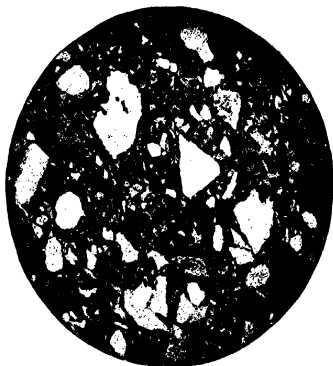
FIG. 18.—" GREYWACKE," SILURIAN (Holywood, Belfast).

Angular quartz grains, with cement of quartz and clay.
Ordinary light.   × 15.

The quartzites and conglomerates which occur at or near the surface of the " High Level " gravel deposits of the coastal side of the Langebergen in southern Cape Colony furnish a characteristic example of siliceous cementation.[2] The deposition of silica is most advanced near the surface of the rock, and

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[1] Phillips, *loc. cit.*, p. 8.

[2] Rogers and du Toit, *Geol. of Cape Colony*, 1909, p. 380.

there is a gradual passage downward into incoherent gravel or sand. In places the original quartz grains assume pyramidal forms by the accretion of new quartz in optical continuity with the old ; but finally, when all interstices have been filled, an intensely hard quartzite is formed in which the divisional lines of individual grains are no longer discernible. A peculiar
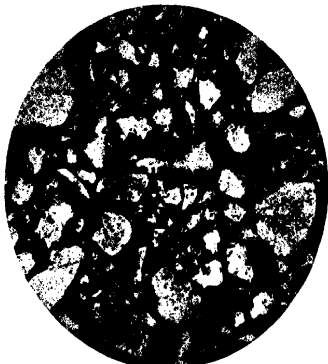
FIG. 19.—FIRECLAY (Glenboig, near Glasgow).

Angular fragments of quartz, with siliceous clay cement.

feature of these surface quartzites is the high polish or veneer presented by the outcrops. On the other hand, the cementing material of the surface quartzites of the Kalahari desert (Botletle sandstone) appears to be chalcedony.[1]

Shales and slates are often silicified by the deposi-

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[1] Passarge, *Die Kalahari, Versuch einer physisch-geographischen Darstellung der Sandfelder des süd-westafrikanischen Beckens,* Berlin, 1904.

tion of secondary silica in their fissures and interstices. The quartz cement appears in the form of minute quartz veins and small interstitial patches, and its presence is further indicated by the high percentage of silica disclosed by chemical analysis. Thus Hutchings [1] found a slate from Tintagel to contain as much as 50 per cent. of silica, although not a single
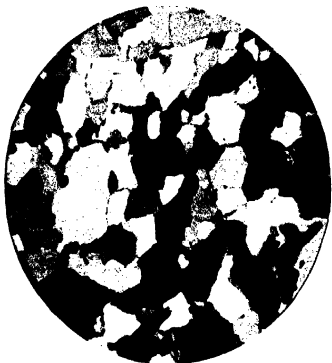
FIG. 20.—QUARTZITE (Loch Torridon, Sutherland).

Sand grains cemented by enlargement with quartz and close interlocking of the grains. Between crossed nicols. × 13.

grain of original (derived) quartz could be detected in a thin section under the microscope.

The silicification of limestones is dealt with under the head of metasomatism, as it is more of a replacement than a cementing process ; but from the fact that the deposition of secondary quartz around detrital

[1] Hutchings, "Notes on the probable Origin of some Slates," *Geol. Mag.*, 1890, p. 319.

quartz grains has been observed in limestones (see p. 204), it is evident that some true cementation also takes place.

The occurrence of the so-called " quartzite dykes " in the Carboniferous Limestone of this country[1] and the Cretaceous of California may be conveniently referred to here (Fig. 21). These curious bodies consist chiefly of detrital quartz grains, together with a small quantity of felspar and mica. The cementing material is chiefly quartz, but is sometimes calcite. The detrital material is considered to have been derived from the overlying beds (in some cases the Millstone Grit, in others the Keuper Sandstone) at the time of their deposition. No doubt the limestone floor on which the beds were being accumulated was seamed with deep fissures which became filled with detrital material and thus produced the steep dyke-like bodies described.

Carbonate of Lime.—Carbonate of lime plays an important rôle as a cementing material. In the case of limestones the rocks become consolidated by a recrystallisation of the original calcareous material rather than by the introduction from without of fresh carbonate of lime. But since the waters circulating in the limestones must be charged with carbonate of lime ready for deposition as calcite in every available opening and interstitial pore, the process must be

    [1] Arnold-Bemrose, " On some Quartzite Dykes in Mountain Limestone near Snelston, Derbyshire," *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 364. Strahan, " Geology of Rhyl," etc., *Mem. Geol. Surv.* (1885), pp. 47-48.

regarded as one of cementation. Examples are
numerous : the Carboniferous Limestone, the Pur-

FIG. 21.—SANDSTONE DYKES (Roaring River,
Northern California).

Cutting Cretaceous shales. The largest is 5 feet wide.
(After J. S. Diller.)

beck Marble, the Forest Marble (Jurassic), and the
Sussex Marble (Cretaceous).

The so-called Dolomitic Conglomerate of the

Mendips is a breccia (of Triassic age) composed of angular to subangular fragments chiefly of Carboniferous Limestone cemented by dolomite or calcite and oxide of iron.

Sandstones also are often cemented by calcite, and are then usually spoken of as *calcareous sandstones*
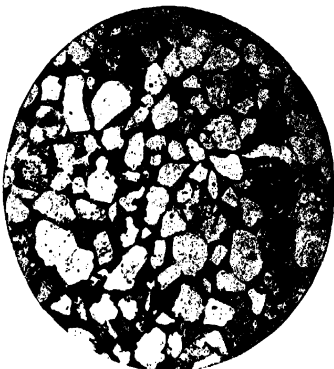
FIG. 22.—CALCAREOUS SANDSTONE (Burntisland, Fife).
Quartz grains cemented by calcite.   Ordinary light.   × 15.

(Fig. 22).   The proportion of calcite cement to quartz sand varies indefinitely ; where the proportion is large (50 per cent. or over) the crystalline form is often perfectly developed, and the sand in such cases is so subordinate as to appear as an impurity in the calcite, as in the well-known case of Fontainebleau, first described by Lassone,[1] and later by Haüy.[2]

[1] Lassone, *Mem. de l'Academie Royale*, Paris, 1775, p. 65.
[2] Haüy, *Traité de Minéralogie*, vol. i, 1822, p. 424.   Compare also A. von Morlot, *Haidingers Berichte*, vol. ii, 1846–47, p. 107.

Similar " siliceous calcites " have been described from the Bad Lands of South Dakota,[1] where they occur in a sandstone (the " White River sandstone ") composed of well-rounded quartz grains completely cemented by calcite. A temporary cessation of the cementation conditions permitted the formation of isolated calcite crystals.

Calcite to the extent of 30 per cent. is the cementing material of the sandstone reefs occurring on the coast of Brazil.[2] The same mineral plays the rôle of cement in the sandstones of the New Red age of this country when they are in the neighbourhood of calcareous inliers of older rocks and in some divisions of the red rocks, even when they are far removed from such calcareous masses.[3] The " Calcareous Grit " of Yorkshire (Corallian) (Fig. 23) is a good example of this type of cementation ; it consists of angular fragments of quartz embedded in a ground-mass of secondary calcite. A similar rock, also of Middle Jurassic age, occurs on the Isle of Eigg. A glauconite sandstone cemented by calcite forms occasional beds in an Upper Jurassic or Lower Cretaceous sand at Shotover Hill near Oxford, and a similar bed is found in the Lower Greensand at Ely.

The dune-limestone of the south coast of Cape

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[1] Penfield and Ford, *Amer. Journ. Sci.*, 4th ser., vol. ix, 1900, p. 352.

[2] Branner, *Bull. Mus. Comp. Zool.*, vol. xliv, 1904.

[3] Thomas, " A Contribution to the Petrography of the New Red Sandstone in the West of England," *Quart. Journ. Geol. Soc.*, vol. lxv, 1909, p. 229.

Colony affords another striking example. The sand-dunes of this coast, where protected from the wind, are invariably covered by a hard cemented crust. A long continuance of the same process carries the cementation many feet in from the surface, and ulti-mately converts the loose sand of the dunes into a

FIG. 23.—CALCAREOUS SANDSTONE (Yorkshire Coast).

Quartz grains cemented by calcite.   Ordinary light.   × 13.

hard rock suitable for use as a building stone.[1]   Similar instances have been described in the Kalahari desert.[2]

The surface limestone or calcareous tufa of the interior of South Africa (which· will be referred to again when dealing with weathered products) often contains so much foreign material (pebbles and sand)

[1] Rogers and du Toit, *The Geol. of Cape Colony*, 1909, p. 398 ; and see also Hatch and Corstorphine, *Geology of South Africa*, 1909, p. 328.
[2] Passarge, *loc. cit.*

derived from the soil that in places it approximates to a rock (calcareous conglomerate and sandstone) formed by cementation rather than by precipitation, thus affording a useful illustration of the relation of the two processes.[1]

Some pisolites, when examined microscopically, either show no definite structure, or present characters indicating that they are in reality fragments of some older limestone which have been rounded by moving water and then cemented together to form a rock. They are, in fact, to be regarded as formed from calcareous sands or gravels, in which the grains or pebbles consist of limestone instead of quartz or other hard minerals and rocks. The softness of limestone is specially favourable to rounding by water action. By increase in the size of the pebbles such deposits graduate into *limestone conglomerates* (see p. 230).

Barium Sulphate and Barium Carbonate. — The earliest description of sandstone cemented by barium sulphate (barytes) appears to have been by Bischof[2] at Munzenberg, Kreuznach, and near Leipzig in Germany.

In the British Isles barium sulphate has been described[3] as a cement in the Keuper sandstone at Bramcote and Stapleford in the neighbourhood of

[1] Rogers and du Toit, *loc. cit.*, p. 401 ; also Hatch and Corstorphine, *loc. cit.*, p. 329. See also Hatch, *Report on the Mines and Minerals of Natal*, 1910, p. 92.

[2] Bischof, *Chem. and Phys. Geology*, vol. i, 1854, p. 433.

[3] Clowes, *Proc. Royal Soc.*, vol. xlvi, pp. 363-8, and vol. lxiv, 1898, p. 374 ; see also *Brit. Assoc. Report* for 1885, p. 1038 ; 1889, p. 595 ; 1893, p. 732.

Nottingham. The barytes is present as a micro-crystalline aggregate either uniformly distributed or aggregated in streaks and patches. In places it amounts to as much as 50 per cent. of the rock, occurring in patches which preserve their optical continuity over large areas, and thus produce a kind of " lustre mott-ling." Its presence has also been noted in the Bunter sandstone of Mere Lake Hill, Staffordshire ; [1] other occurrences have been reported at Prenton, Bidston,[2] Alderley Edge, Oxton, Storeton, and West Kirby, all in the Triassic sandstone of Cheshire and adjoining counties ; [3] and it has been observed in the Triassic sandstone of the coast of Elginshire,[4] and in the Scottish Carboniferous sandstones.[5]

A chemical examination of the Keuper sandstone of Beeston Castle, Cheshire, by Mr. H. T. Brown has shown that the cement in this rock is not the sulphate (as had been described [6]), but the carbonate of barium.[7] Clowes inclines to the belief that in all cases the original cementing material was not a sulphate, but a carbonate (witherite) deposited from water in which it was dissolved as a bicarbonate, and

[1] Wedd, " Note on Barium Sulphate as a Cementing Material in Stone," *Geol. Mag.*, 1899, p. 508.

[2] Moore, " A Chemical Examination of Sandstones from Prenton Hill and Bidston Hill," *Proc. Liverpool Geol. Soc.*, vol. viii, 1898, p. 241.

[3] *Proc. Roy. Soc.*; vol. lxiv, 1898–9, p. 376.

[4] Mackie, *Rep. Brit. Assoc.*, 1901, p. 649.

[5] Bosworth, *Rep. Brit. Assoc.*, 1912.

[6] Strahan, " Geology of the Neighbourhood of Chester," *Geological Survey Memoir*, 1882, pp. 7, 8.

[7] Clowes, *Rep. Brit. Assoc.*, 1889, p. 594.

that the sulphate has been formed by a metasomatic interchange with soluble sulphates. It should be borne in mind, however, that, as Bischof has pointed out, barium sulphate may be deposited directly by the cooling of thermal waters containing both barium carbonate and sodium sulphate in solution. An entirely different explanation is offered by G. Mackie.[1] He ascribes the presence of barium sulphate in the Triassic sandstone to the concentration of the waters of an inland lake in which, together with other salts, this substance was present, the deposition taking place in the order of insolubility of the dissolved salts. In all cases the original source of the barium is in the felspars and micas of the crystalline rocks, from which it is liberated in the zone of weathering.

The insolubility of barium sulphate gives a great power of resisting weathering to those parts of the sandstone that are cemented by it, so that ribs and peaks remain as projections long after the ordinary sandstone has been removed by erosion. The origin of the great pillar known as the Hemlock Stone near Nottingham is due to this cause ; and Watts ascribes to it the survival of the curiously isolated stack of rock known as the Peakstones Rock near the village of Alton in Staffordshire.[2] In the case where the cemented masses are spheroidal, the washing away of the uncemented sand causes an accumulation of

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[1] *Loc. cit.*, p. 650.
[2] Watts, " On a Keuper Sandstone cemented by Barium Sulphate," *Rep. Brit. Assoc.*, 1894, p. 665, and *Geol. Mag.*, 1894, p. 510.

pebble-like bodies liable to confusion with pebble-beds, as has been the case near Nottingham.

Instances are also known of the formation of isolated crystals of barytes (the so-called " sand-barytes ") containing from 44 to 55 per cent. of sand. Such crystals and groups of crystals are found in the Nubian sandstone of Kharga in Egypt, which in places is cemented by barium sulphate.[1] Barytes as a cementing material of the Carboniferous " fireclays " of Northumberland (Seaton) has been described by Hutchings.[2]

Sulphate of Lime.—Gypseous sandstone, in which the cementing material is the hydrated sulphate of lime (gypsum), has a wide distribution in the Sahara, as at Ghadamés.[3] It has also been described from the Kirghiz and Astrakhan Steppes,[4] from the Cariote in Bolivia,[5] and from Sussex, New Brunswick.[6] In all these cases the gypsum tends to form large crystalline masses, sometimes with definite crystal shapes, enclosing as much as 60 per cent. of sand, like the well-known sand-calcites of Fontainebleau.

The so-called Brockram of Appleby and Kirkby Stephen is a breccia of Permian age in which fragments

[1] Pogue, *Proc. U.S. Nat. Mus.*, vol. xxxviii, 1911, p. 17.

[2] Hutchings, *loc. cit.*, p. 266.

[3] Delesse and De Lapparent, *Revue de Géol.*, vol. xiv, 1878, p. 58; vol. xvi, p. 48, *ibidem*.

[4] Doss, *Zeitsch. der deutsch. Geol. Gesell.*, vol. xlix, 1897, p. 143.

[5] Pöhlmann, *Verh. deutsch. Wissensch. Ver.*, Chili, vol. ii, 1892 ; see also *N. Jahrb. für Min.*, 1894, vol. i, p. 59.

[6] *Amer. Journ. Sci.*, vol. xxxv, 1863, p. 213.

of Carboniferous Limestone are held together by a gypseous cement.

Sulphate of Strontium. — Sulphate of strontium (celestine) has been recorded as a cement in the Upper Marls of Peake and Salcombe Hills, near Sidmouth.[1] It has also been observed as a cement in the nodular portions of a sandstone near Oppenheim in Rhein-hessen.[2]

Calcium Fluoride. — Calcium fluoride (fluorspar) occurs as the cementing material of a Triassic sand-stone at Cummingstone in Elginshire, some of the material containing as much as 26 per cent. of this cement.[3] The fluorite occurs disseminated through the sandstone in small white patches showing " lustre mottling," due to the parallelism of the closely-packed cubes in which the mineral is crystallised. In other parts of the sandstone it is confined to definite layers or bands.

Oxides of Iron.—Ferruginous cements (hæmatite and limonite) are common in the Old Red, Permian, Triassic, and Lower Cretaceous sandstones (Fig. 24). The iron oxide is often present as an investing pellicle around each quartz grain ; and where silicification has subsequently taken place the iron coating often becomes enclosed by the new crystal growth. On the other hand, the secondary quartz itself sometimes

[1] Perceval, quoted by Thomas, *loc. cit.*

[2] Gergens, *N. Jahrb. für Min.*, 1855, p. 172.

[3] Mackie, " The Occurrence of Barium Sulphate and Calcium Fluoride as Cementing Substances in the Elgin Trias," *Rep. Brit. Assoc.*, 1901, p. 649.

becomes coated with iron oxide, and successive periods
of ferruginous and siliceous cementation may be thus
distinguished. Good examples of cementation by iron
oxides occur among the recent gravels and sands of
South Africa, which are sometimes hardened by this
process to such an extent that when struck by the
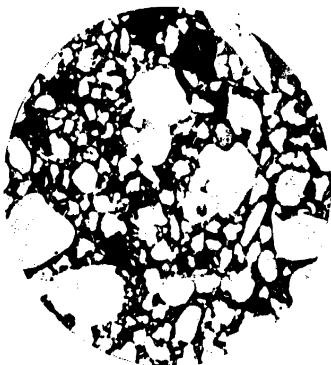
FIG. 24.—FERRUGINOUS SANDSTONE, CARSTONE
(Potton, Bedfordshire).

Quartz grains cemented by limonite. Ordinary light.   × 15.

hammer they break across pebbles and matrix with
equal facility.[1]

Carbonate of Iron.—Although chalybite (carbonate
of iron) is found playing the part of a cement (as in
the Kelloways rock of Scarborough), such occurrences
belong rather to metasomatism than cementation,

[1] Rogers and du Toit, *The Geol. of Cape Colony*, 1909, p. 377 ;
see also Hatch, *Report on the Mines and Minerals of Natal*, 1910,
p. 73.

since the carbonate of iron has, probably in all cases, replaced an original calcium carbonate cement.

Sideroplesite (a hexagonal carbonate, intermediate in composition between chalybite and dolomite) is found in spherical and lozenge-shaped forms in certain Carboniferous fireclays. According to Gregory, how-
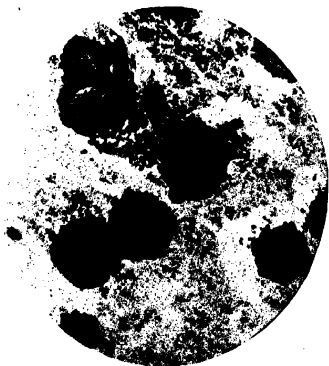
Fig. 25.—SIDEROPLESITE IN FIRECLAY (Glenboig, near Glasgow)
Ordinary light. × 15.

ever, this mineral was precipitated during the deposi· tion of the clay from the waters of an inland sea or lagoon [1] (see Fig. 25).

Metallic Ores.—The ores of the metals act as cements, especially in brecciated veins where fragments of the vein walls are often knit together by the ore.

[1] Gregory, *Proceedings Royal Soc. Edinburgh*, vol. xxx, 1910, p. 359 ; see also Hatch, *Report on the Mines and Minerals of Natal*, 1910, p. 73.

They are also found cementing the component grains of true sediments such as sandstone. Thus at Alderley Edge in Cheshire, a lead ore has been worked which consists of Keuper sandstone cemented by galena, the latter occurring as large crystal units in the sandstone, broken surfaces of which exhibit lustre mottling over large areas.

The Clastic Constituents of the Cemented Rocks. —Since these rocks are formed by the cementation of the incoherent sediments, the latter constitute their clastic constituents, and most of what has been written in Chapter II will apply here.[1] The same limits of size may be used to distinguish between conglomerate, sandstone and clay-stone, mud-stone and shale, as are used to differentiate pebbles, sand, and mud.

Conglomerates.—With regard to the conglomerates, their constituent pebbles may be of any material, and any particular conglomerate may be made up of a great variety of pebbles, or may (although more rarely) be composed of only one kind of pebble. On account of its resistant quality quartz is very common, the pebbles of this mineral being derived from the disintegration of older pebble-beds, from acid igneous rocks, from gneiss, or from vein-quartz. Where chert or flint beds have been available, the resulting conglomerates are largely made up of these materials

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[1] An excellent account of the constituents of British cemented sediments is given by Bonney, *Presidential Address to Section C, Brit. Ass.*, Birmingham, 1886.

(Fig. 26). Quartzites are also commonly represented, and all types of igneous rocks may be found among the pebbles. An interesting example of how varied the pebbles of a conglomerate may be is furnished by the arkose pebble-beds of the Torridonian sandstone in the north-west Highlands. An examination of these

FIG. 26.—HERTFORDSHIRE PUDDING-STONE.

Flint-pebbles and sand cemented by granular quartz.
Crossed nicols.   × 7.

rocks by Teall[1] showed that they comprise vein-quartz (50 per cent.), quartzites, showing contact alteration, black and yellow cherts, jasper with spherulitic structures indicating an origin by silicification of rhyolites of the Lea Rock (Wrekin) type, and spherulitic felsites similar to those of Uriconian age in Shropshire.

[1] Teall, " Geological Structure of the North-West Highlands,"
Mem. Geol. Surv., 1907, p. 279.

The finer clastic material of pebble-beds is of similar constitution to that which composes the sandstones, and needs no special description (see p. 197).

Among the pebbles composing the coarser beds of the Millstone Grit of Yorkshire are fragments of gneiss, mica-schist, granite, quartz-porphyry and felspar-porphyry, together with pegmatite and felspar (microcline). The most abundant heavy minerals in the finer material are zircon and garnet.[1]

An excellent example of grits and conglomerates composed of fragments of a large variety of rocks is afforded by the coarser beds of the Ingletonian series of West Yorkshire.[2] These strata, to which a pre-Cambrian age has been assigned, consist essentially of subangular and rounded fragments of very diverse character. There are many simple fragments of quartz, felspar, and other minerals, but the larger elements consist almost exclusively of fragments of igneous and metamorphic rocks that must for the most part have been derived from an area of crystalline schists. They include quartzite, granulite, quartz-schist, various gneisses, phyllite, and slate, together with granite, granophyre, syenite, quartz-porphyry, porphyrite, rhyolite, trachyte, and andesite. The whole rock has acquired a general greenish tinge by development of secondary chlorite, which may be

[1] Gilligan, *Rep. Brit. Assoc.*, Dundee, 1912, and *Quart. Journ. Geol. Soc.*, vol. lxxv, p. 251.

[2] Rastall, "The Ingletonian Series of West Yorkshire," *Proc. Yorks. Geol. Soc.*, vol. xvi, 1906, pp. 87-100.

to some extent derived from original mica, but was doubtless for the most part introduced during cementation.

In the Permian Brockram nearly all the pebbles and fragments are of Carboniferous limestone, the few exceptions being fragments of veinstone, hæmatite, sandstone, and quartzite, the latter especially in the Upper Brockram.

A special type are the Permian limestone conglomerates or breccias of the Severn basin, which are largely composed of fragments of limestones of various ages—Carboniferous to Silurian (Wenlock and Woolhope[1]). The imperfect rounding of the fragments implies transport over great gravel-fans at the foot of hill-ranges by streams loaded with debris, and under conditions of slope and shape of bed precluding the rounding by abrasion typical of mountain streams.[2]

Sandstones. — In the sandstones quartz is the dominant detrital mineral. In some varieties, however, felspar plays an important part, and such rocks are distinguished as *felspathic sandstone* or *arkose* (Fig. 27). Mica (both muscovite and biotite) is also a common detrital constituent, and in some varieties is present in such abundance as to justify the application of the term *micaceous sandstone*. Other components are subordinate, and are only discoverable by a microscopic examination of the residue after the

[1] King, " The Permian Conglomerates of the Lower Severn Basin," *Quart. Journ. Geol. Soc.*, vol. lv, 1899, p. 97.

[2] Oldham, " The Permian Breccias of the Midlands," *Quart. Journ. Geol. Soc.*, vol. l, 1894, p. 465.

removal of the quartz, felspar, and mica by levigation in water, or by the use of heavy solutions. They consist of such resistant minerals as were able to survive the weathering processes that effected the destruction of the rocks in which they originally occurred. Among them the following minerals have been recorded :
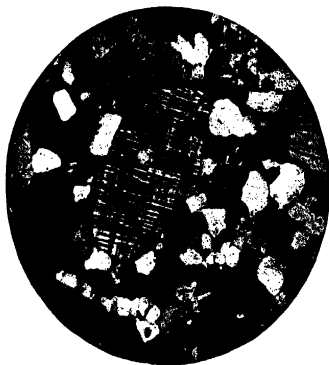
FIG. 27.—ARKOSE, FELSPATHIC SANDSTONE
(Loch Torridon, Ross-shire).

The large cross-hatched grain is microcline felspar ; the remaining grains are quartz ; the cement is siliceous (quartz). Between crossed nicols. × 13.

magnetite, ilmenite, rutile, anatase, brookite, fluorspar, apatite, garnet, tourmaline, zircon, staurolite, kyanite, actinolite, topaz, and sphene.

Important deductions can sometimes be made from the mineral association of these rarer detrital constituents. Thus H. H. Thomas,[1] in describing

[1] Thomas, " Petrography of the New Red Sandstone," *Quart. Journ. Geol. Soc.*, vol. lxv, 1909, p. 242.

the New Red sandstones of Devon and Somerset, deduces, from the great abundance in certain of them of such minerals as blue tourmaline, topaz, garnet, rutile, and brookite, that they were largely derived from the granite masses of Devon and Cornwall and their attendant metamorphic rocks and veinstones. The same author's examination of the fine material of the great Bunter pebble-bed of Budleigh Salterton on the south coast of Devon led him, on the other hand, to the conclusion that the mass of the material was furnished by a highly-metamorphosed area, differing widely from any now exposed in the south-west of England, and that the probable source was the Armorican *massif*, which in Triassic times probably extended north-west from Brittany to the south-west of England.[1]

An investigation of the Scottish Carboniferous sandstones shows that they always contain detrital zircon, magnetite, tourmaline, rutile, and staurolite. Anatase is occasionally found, and garnet is either abundant or entirely absent. The sands containing abundant angular garnet are obviously derived from the Highland schists, while those devoid of garnet probably came from the north-east, east, and south.[2]

The finer material of the arkose - beds of the Torridonian sandstone, besides quartz and felspar,

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[1] Thomas, " The Mineralogical Constitution of the Bunter Pebble-Bed," *Quart. Journ. Geol. Soc.*, vol. lviii, 1902, p. 620. See also Bonney, *Geol. Mag.*, 1895, p. 75, and *Quart. Journ. Geol. Soc.*, vol. lvi, 1900, p. 287.

[2] Bosworth, *Brit. Assoc. Rep.*, Dundee, 1912.

contains lines of heavy minerals, such as magnetite, ilmenite, sphene, garnet, tourmaline, zircon, and rutile. The dominant felspars are microcline and microcline-microperthite, but orthoclase and oligoclase also occur. The quartz grains show " strainshadows," or undulatory extinction, when a thin section is rotated between crossed nicols, thus indicating a derivation from rocks that have undergone deformation.[1]

According to Peach [2] these Torridonian sediments form part of a continental deposit derived from and laid down on an old land surface, of which the Archæan rocks of the north-west Highlands are a remnant.

As an extreme case Watson and Hess have described a sandstone from Virginia consisting almost exclusively of zircon and ilmenite, cemented by limonite with only a few grains of quartz.[3]

Clays, Mudstones, and Shales.—As regards their clastic constituents, these rocks are identical, the names simply indicating structural differences. The term " mudstone " is applied to a consolidated clay or mud rock which presents no fissile structure, while the term " shale " is used when there is a lamination parallel to the planes of sedimentation. A third term —" slate "—is restricted to rocks of the same origin and composition, in which a slaty cleavage has been

[1] Teall, " Geological Structure of the North-West Highlands," *Mem. Geol. Surv.*, 1907, p. 284.

[2] Peach, *Presidential Address to Section C, Brit. Assoc.*, Dundee, 1912.

[3] *Bulletin* 530 P, *U.S. Geol. Surv.*, 1912.

developed by pressure in a direction not necessarily coincident with, and indeed generally oblique to, the planes of sedimentation (see p. 280).

The detrital constituents of these rocks differ but little as regards kind from those of the sandstones. They are, however, in a state of more minute subdivision, which often renders their separation and determination a matter of some difficulty. There is no doubt, however, that the mineral quartz plays the dominant rôle. Felspar also occurs, although frequently replaced by its decomposition products, sericite, calcite, etc. Micas, both muscovite and biotite, occur as primary constituents, but a large proportion of the muscovite is of secondary origin. The biotite also is often replaced by epidote ; while chlorite is present as a derived constituent. Limonite and calcite are common secondary products. Pyrites, marcasite, and pyrrhotite are frequent constituents, and no doubt owe their origin to a reduction of iron salts by organic compounds. The presence of the latter is indicated in many of these rocks as black carbonaceous matter. Many of the resistant minerals already enumerated as occurring in sandstones are also found in shales. Detrital rutile occurs ; but much more abundant are fine needles of this mineral (the so-called " clay slate needles "), that have probably been formed as a secondary product from the titanic acid set free by the decomposition of biotite.

On account of the minute state of subdivision of the materials composing the clays and shales, their

fine-textured base was formerly considered to con-
sist of a special "clay substance," which, on the
strength of chemical analysis, was supposed to be
kaolin, the name given to a hydrated silicate of
aluminium, of the composition represented by the
formula $Al_2O_3 . 2SiO_2 . 2H_2O$.   But the researches of
Hutchings [1] have shown that the "paste" of these
rocks consists in reality of a fine flour of quartz and
felspar, together with a large proportion of secondary
muscovite (sericite) formed by the decomposition of
the felspar (orthoclase).   Hydrated silicates of alumina
(kaolin or halloysite) may or may not be present, but
the presence of definitely crystallised kaolinite is
incapable of proof.   Writing on the Coal Measure
"fireclays" [2] of Northumberland, Hutchings says,[3]
"the very thinnest possible films show under a good
$\frac{1}{8}$-inch objective a minutely-granular substance, usually
of very faint yellowish tinge, and of such extreme
tenuity that in polarised light it is either quite inactive
or depolarises only just perceptibly in a faint ' speckly '
manner.   This granular matter is, I suppose, the
mixture usually spoken of as ' kaolin.' [4]   As soon as
we examine a film, a little thicker, but still extremely
thin, we see between crossed nicols a more distinct

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[1] Hutchings, *Geol. Mag.*, 1890, pp. 264, 316. Cox, *ibid.*,
1918, p. 56.

[2] Clays which, owing to a low alkali-content, can be exposed
to a high temperature without melting.

[3] Hutchings, *loc. cit.*, p. 271.

[4] Gregory (*Proc. Royal Soc. Edin.*, vol. xxx, p. 354) suggests
that this material is the amorphous mineral halloysite having the
composition $Al_2O_3 . 2SiO_2 . 2H_2O$.

depolarising action of the granular matter itself, and also the presence of more or less numerous extremely small flakes of a micaceous mineral. In films a little thicker still, we usually soon reach a point where the action of the granular matter is obscured by the depolarisation of this mica, much of which, when mounted in balsam, cannot be made out at all in ordinary light." The mica, quartz, and felspar particles (quite apart from the coarse sand grains and larger flakes of mica) much exceed in quantity the so-called "kaolin." "The plasticity of such clays seems to depend largely on the fineness of the particles ; also probably on their physical nature connected with the hydration of the mica, because of all these clays it is true, as it is of more kaolinitic clays, that as soon as they are dehydrated, they are no longer plastic."

Detrital and other Primary Constituents of the Limestones.—Besides the organically - formed carbonates of the limestones and dolomites, there are always present, even if in restricted proportions, some primary minerals of detrital origin. L. Cayeux[1] found the primary minerals of the Chalk of the Paris basin to consist of quartz, zircon, tourmaline, rutile, magnetite, orthoclase, plagioclase, anatase, brookite, staurolite, garnet, apatite, corundum, ilmenite, and kyanite, in

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[1] Cayeux, " Contribution à l'étude micrographique des terrains sédimentaires," *Mém. Soc. Géol. Nord*, vol. iv, 1897, pp. 1-589, summarised in *Ann. Soc. Géol. Nord*, vol. xxvi, 1897, pp. 168-87. A memoir in two parts, 1st, *Some Mesozoic and Tertiary Siliceous Sediments of the Paris Basin and of Belgium* ; 2nd, *The Chalk of the Paris Basin.*

grains having a diameter of less than 0.1 mm., and constituting not more than 1 per cent. of the total.

An examination by Wethered [1] of the residues, obtained by treating with hydrochloric acid various members of the Inferior Oolite of the Cotteswold Hills, showed that they consist chiefly of detrital quartz together with felspars (orthoclase, microcline, and plagioclase), zircon, tourmaline, and rutile. The latter mineral occurs in minute crystals in the Oolite Marl, and is similar to its well-known occurrence in shales and slates (see p. 201). The residue obtained by a similar treatment of the Carboniferous limestone of Clifton was examined by the same author,[2] and found to consist of detrital quartz with secondary enlargements, in some cases to perfectly-formed crystals, together with felspar, tourmaline, and zircon.

But, besides the above-mentioned minerals, as to the detrital origin of which there can be no doubt, there is in many limestones much material which, although calcareous, presents no trace of organic structure. This is regarded by some authors as resulting from the detrition of older limestones.[3] The opponents of this view regard the structureless paste of such limestones as having been formed by chemical precipitation under the special conditions prevailing

[1] Wethered, " The Inferior Oolite of the Cotteswold Hills," *Quart. Journ. Geol. Soc.*, vol. xlvii, 1891, p. 550.

[2] Wethered, " On Insoluble Residues obtained from the Carboniferous Limestone Series at Clifton," *Quart. Journ. Geol. Soc.*, vol. xliv, 1888, p. 186.

[3] Sorby, " Pres. Address," *Proc. Geol. Soc.*, 1879, p. 56.

at the time of their formation.[1] There can be no doubt that the destruction of coral reefs by breaker action and the distribution of the resulting calcareous mud over the sea-floor accounts for the presence of much of the calcareous paste in littoral deposits of Tertiary or Recent ages (see p. 131). Similar mechanically derived limestones are formed as shallow-water sediments wherever large masses of calcareous rocks are undergoing detrition. Such appears to be the origin of many nodular and perhaps of some pisolitic limestones, such as the Cornstones of Old Red sandstone age and of the fine-grained Liassic limestones of Dorsetshire.[2] In shelly limestone and crinoidal limestone, on the other hand, the detrital material is largely of organic origin.

Goodchild,[3] after a careful review of the evidence, concludes that all limestones are of compound origin, being partly organic, partly detrital, and partly formed as chemical precipitates under the influence of organic agents.

Metasomatism.—Great masses of sediments may, under the influence of metasomatism, be so altered that none of the original mineral or minerals remain. Since these changes are brought about under the influence of circulating water, the extent to which the alteration can take place is a function of the

[1] Prestwich, *Geology*, vol. ii, p. 320.
[2] Woodward, " Excursion to Lyme Regis," *Proc. Geol. Assoc.*, vol. xix, 1906, p. 327.
[3] Goodchild, " The Paste of Limestones," *Geol. Mag.*, 1890, p. 73.

porosity of the rock. Thus in dense rocks with only sub-capillary openings very small changes take place, even after immense lapses of time ; and minerals such as felspar and augite, which, where exposed to the action of circulating water, are exceedingly prone to alteration, are often found still almost perfectly fresh even in pre-Cambrian rocks (as, for instance, in the Lake Superior district).[1]

Other factors that influence metasomatism favourably are fineness of grain and a high temperature. Thus, for instance, metasomatism is promoted in the neighbourhood of igneous intrusions by the increased activity of the circulating solutions under the influence of the heat given off during their cooling.

A characteristic feature of rocks that owe their present composition to metasomatism is the preservation of the original rock-structures. Thus certain iron-ores formed by the substitution of carbonate of iron for calcium carbonate in oolitic limestone reproduce perfectly the oolitic structure. Similarly planes of bedding, joints and faults, folds and fossils, are all found preserved in the altered rock. The textures, both of sedimentary and igneous rocks, are reproduced even when the change has been complete. An interesting instance of this has been described on the Witwatersrand in the Transvaal, where in the Meyer and Charlton mine a portion of the auriferous conglomerate, known as the Main Reef, has been so affected that both quartz pebbles and siliceous cement

[1] Van Hise, *A Treatise on Metamorphism*, p. 641.

are entirely replaced by calcite, but without obliteration of the conglomerate structure.[1]

The most important metasomatic changes affecting the sediments are : silicification, dolomitisation, replacement of carbonate of calcium by carbonate of iron or limonite, phosphatisation and pyritisation.

Silicification.—The silicification of limestones, in which the carbonate of calcium is replaced by silica, generally in the form of chert, is very common. The silica in this case is largely derived from organic remains (sponge-spicules, the frustra of Diatoms, Radiolaria, etc.) in the limestones, and the process consists in its solution, segregation, and re-deposition. Hinde[2] has described a case at Spitsbergen and Axels Island where whole calcareous formations, some seven or eight hundred feet in thickness, have been almost completely changed to chert, and Hull, in describing the beds of chert in the Upper Carboniferous limestone of Ireland, states that in places, as for instance at the foot of the ridge west of Carlow, the limestone for a thickness of 30 or 40 feet is completely replaced by thinly-bedded chert.[3] The flints in the Chalk and the chert of the Upper Greensand of the Carboniferous Limestone and of the Portland beds are other familiar instances (Fig. 28).

[1] Kuntz, *Trans. Geol. Soc. S.A.*, vol. vi, 1903, p. 74.

[2] Hinde, " On the Chert and Siliceous Schists of the Permo-Carboniferous Strata of Spitsbergen," *Geol. Mag.*, 1888, pp. 241-251.

[3] Hull, *Sci. Trans. Roy. Dub. Soc.*, vol. i (new series), 1878, p. 75.

In the metasomatic replacement of the sponge-
beds of the Upper and Lower Greensand of the
Wealden area, the Isle of Wight and the south-western
counties, so admirably described by Dr. Hinde,[1] both
silica and carbonate of lime have played a part (Fig.
29). These sponge-beds, locally known as malm-

FIG. 28.—SPONGE-SPICULES (in the Upper Greensand
of Warminster).

(After Hinde.)

stone, hearthstone, firestone, and chert, consist to a
large extent of the detached spicular remains of siliceous
sponges, intermingled with grains of quartz - sand,
glauconite, and, in the case of the malmstone or hearth-
stone, scales of silvery mica. The original amorphous
silica of the sponge remains has, as a rule, been dis-

[1] Hinde, " On Beds of Sponge Remains in the Lower and
Upper Greensand of the South of England," *Phil. Trans. Roy.
Soc.*, 1885, pt. ii, p. 403.

solved out, leaving the casts of the spicules empty
or refilled by calcite, glauconite, ferric oxide, or
chalcedony. The matrix of the sponge-beds of the
malmstone and firestone consists to a large extent
of colloidal and amorphous silica, derived from the
sponge-spicules and deposited in the form of minute
globules. In the softer and more friable beds, the

FIG. 29.—COLLOIDAL SILICA (filling sponge-spicules
in malmstone, from Merstham).
× 150. (After Hinde.)

siliceous globules, of which they are very largely
composed, are but lightly held together, but in the
harder nodular portions they are cemented by chal-
cedonic silica. In some places, as in the Lower
Greensand at Maidstone, Tilburstowe Hill, and Hythe,
and in the Upper Greensand at Selborne, the spicules
are replaced by calcite, and this material also occurs

P

in a granular or crystalline aggregate in the matrix of the rock. It has no doubt been derived from remains of Foraminifera and other organisms.

In the case of chert, the ground-mass consists of chalcedonic, and sometimes also of crystalline, silica, in which are numerous sponge-spicules, also of chalcedony, together with fragmentary Foraminifera, pieces of Echinoderms, and grains of quartz-sand. The chalcedonic silica of the ground-mass is deposited in concentric layers around these fragments, and under the microscope it presents a radiate-fibrous structure. Dr. Hinde disputes the view that the silica is derived directly from sea-water, and says: " There can scarcely be room for doubting that the beds and irregular masses of chert, which are found nearly everywhere in the strata of the Lower and Upper Greensand in connection with the detached spicules of sponges, have been derived from the silica of these sponge-remains, and from the same source has also originated the silica, which in many of the deposits— more particularly in the Blackdown Hills—has replaced the shells and tests of the mollusca and other calcareous organisms."

Messrs. Jukes-Browne and W. Hill [1] have shown that in the Lower Chalk of Berkshire and Wiltshire there are also beds containing a large amount of disseminated colloidal silica, which, as in the case

[1] Jukes-Browne and Hill, " On Colloid Silica in the Lower Chalk of Berkshire and Wiltshire," *Quart. Journ. Geol. Soc.*, vol. lxv, 1889, p. 403.

of the malmstones of the Upper Greensand, has been derived from sponge - spicules. This silica occurs largely in the amorphous globular form, but nodular masses of Chalk occur which are permeated and cemented by chalcedonic silica. They conclude from their observations that the globular silica was precipitated from solution before the consolidation of the beds and while they were still permeated by sea-water, and they state their belief that the malmstones of the Upper Greensand were formed in a similar way. They also are disposed to regard the nodular concretions of the Cretaceous beds, such as those of flint and chert, as having been formed by a replacement of carbonate of lime by silica, which began soon after the deposition of the sediment on the sea-bottom.[1] Writing on the subject of flints in 1880, Sollas [2] stated his belief that they had been formed by the gradual elimination of the calcareous matter from a mass of siliceous chalk and its replacement by silica. Thus he says : " A deposit of sponge-spicules accumulated in the chalk ooze, and in the presence of sea-water under pressure entered into solution. Replacement of the calcareous material of the ooze then ensued ; small shells, and many large ones too, being converted into silex ; and siliceous chalk, not flint, was the result. The chambers of the Foraminifera and the interstices of the chalk were now

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[1] Jukes-Browne and Hill, loc. cit. See also Quart. Journ. Geol. Soc., vol. lii, 1896, p. 122. Hill, " Flint and Chert " (Pres. Add.), Proc. Geol. Assoc., vol. xxii, 1911, pp. 61-94.

[2] Sollas, Ann. Mag. Nat. Hist., ser. 5, vol. vi, 1880, p. 449.

filled up by a simple deposition of silica, and the siliceous chalk became converted into black flint, an incompletely silicified layer of chalk remaining as the white layer of its surface."

The dolomite formation of South Africa, which is so widely distributed in the Transvaal and in Griqualand West, is in places extremely silicified,[1] the replacing silica being in part chalcedony, in part quartz. Usually the silicified beds are of the nature of chert, but occasionally the altered rock is indistinguishable from an ordinary quartzite.[2]

Rutley[3] regards the Arkansas novaculite, a variety of whetstone, as a siliceous replacement of a dolomitic limestone. This rock is composed almost entirely of silica in the form of minute particles, which, on account of the specific gravity of the rock, Rutley regards as chalcedony rather than quartz, although the particles are too minute for definite optical determination.

Radiolarian chert is a rock formed by siliceous cementation (possibly accompanied by metasomatism) of a siliceous ooze, chiefly composed of Radiolaria and probably of deep-water origin. It is frequently associated with pillow-lavas (see Vol. I, p. 28), as, for instance, on Mullion Island,[4] near the Lizard in

[1] Hatch. " A Geological Survey of the Witwatersrand," *Quart. Journ. Geol. Soc.*, vol. liv, 1898, p. 89, and Hatch and Corstorphine, *The Geology of South Africa*, 1909, p. 176.

[2] Young, *Trans. Geol. Soc. S. Africa*, vol. ix, 1906, p. 59.

[3] Rutley, " On the Origin of certain Novaculites and Quartzites," *Quart. Journ. Geol. Soc.*, vol. l, 1894, p. 377.

[4] Fox and Teall, " On a Radiolarian Chert from Mullion Island," *Quart. Journ. Geol. Soc.*, vol. xlix, 1893, p. 211.

Cornwall, and at the base of the Moffat Shales of the Southern Uplands of Scotland. Radiolarian cherts are also found in conjunction with thin black limestones of deep-water character in the Lower Carboniferous (Lower Culm) of North Devon.

Calcification. — The replacement of quartz by calcite is a case of metasomatism not commonly met

FIG. 30.—RADIOLARIAN CHERT (Devonport, Devonshire).

(Photograph by Geol. Survey.)

with, but it has been clearly proved to have taken place in the auriferous conglomerates of the Witwatersrand, where calcite is found in all stages of replacement of quartz, whether occurring as pebbles or as cementing material.[1] In the Meyer and Charlton mine, where the calcification permitted of

[1] Kuntz, *Trans. Geol. Soc. of S. Africa*, 1903, p. 14, and Young, *ibid.*, vol. x, 1907, p. 27.

close study, it was found to have proceeded from the narrow fissures which furnished the supply of carbonated water. The alteration of the pebbles takes place from without inwards, advantage being taken of existing cracks. The replacing calcite is coarse-grained, and several individuals of quartz are often replaced by one individual crystal of calcite, but, on the other hand, several individuals of calcite are also found replacing a single individual of quartz.

Dolomitisation.—The replacement of the carbonate of calcium in limestones by the double carbonate of calcium and magnesium (dolomite) is also a common metasomatic phenomenon.

Limestones of organic origin consist primarily almost entirely of calcium carbonate, and the bulk of the magnesium found in dolomitic limestones owes its presence there to metasomatic replacement at some period subsequent to the formation of the rock. The change may commence at the moment of deposition, or it may commence below sea-level and be completed when the rock has been raised above the sea and become a part of the land; or, again, the whole of the dolomitisation may be subsequent to elevation.

It is well known that reef-limestones are specially liable to dolomitisation, and that this applies to both ancient and modern coral reefs. It is evident, therefore, that the metasomatic process takes place soon after the formation of the reef, if indeed not concurrently with it. The material obtained from a deep boring in the atoll of Funafuti, examined by

Prof. Judd and Dr. Cullis, was found to be highly dolomitic,[1] and the same is the case with many of the raised reefs of the Pacific and Indian Oceans,[2] some of which nearly approach pure dolomite rock in composition. In an investigation of the subject in connection with the dolomite rocks of Southern Tyrol, Prof. Skeats[3] finds that the conditions favourable to the formation of dolomite masses from coral reefs are :

(a) Shallow water between o and 150 feet in depth, corresponding to a pressure of 1 to 5 atmospheres.

(b) The presence of carbon dioxide in comparative abundance, causing the partial solution of the limestones and the possibility of chemical interchange with the magnesium salts in sea-water.

(c) Porosity of the limestones, allowing of the percolation of sea-water through the mass of the rocks.

(d) Sufficiently slow subsidence or elevation to render complete the change from calcium carbonate to the double carbonate of calcium and magnesium.

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[1] "The Atoll of Funafuti," *Report of the Coral Reef Committee of the Royal Society*, London, 1904.

[2] Andrews, *A Monograph of Christmas Island*, London, 1900 (Note by E. W. Skeats on the Composition of some Dolomitic and other Limestones, on pp. 265-8).

[3] Skeats, " On the Chemical and Mineralogical Evidence as to the Origin of the Dolomites of Southern Tyrol," *Quart. Journ. Geol. Soc.*, vol. lxi, 1905, pp. 97-139.

No doubt the dolomitisation of the coral reefs is facilitated by the fact that the calcareous skeleton of corals consists of aragonite, which is less stable than calcite, and therefore more readily attacked by solutions containing salts of magnesium.

We have now to consider the dolomitisation of limestones, which takes place subsequently to the elevation of the rock above sea-level.

Since magnesium salts are introduced into such limestones by means of circulating water, this type of dolomitisation is favoured by orogenic movements and fracturing, which produce openings into which the solutions can penetrate. The magnesium is derived in great part from the ferro-magnesian silicates of igneous rocks ; but it is also derived from a large number of secondary minerals, such as talc, chlorite, serpentine, and the various zeolites that occur both in igneous and in sedimentary rocks. Set free by the decomposition of these minerals in the zone of weathering, it goes into solution in the form of carbonate and sulphate,[1] a part being carried down to the belt of cementation, while the remainder is transported by the overland circulation to the sea, in which the quantity of magnesium salts is thus being constantly augmented.[2]

The replacement of calcite by dolomite involves

[1] The introduction of magnesium in the form of sulphate explains why gypsum is a frequent constituent of dolomitic limestone : it results from the interaction of magnesium sulphate and calcium carbonate.

[2] Parsons, *Geol. Mag.*, 1918, p. 246, and 1922, p. 51.

a contraction of volume amounting to 12.3 per cent. ; consequently, dolomitisation tends to produce a porous rock. This porosity, however, is destroyed in regions of strong orogenic movement, or where much re-crystallisation takes place. Since the replacement of carbonate of calcium by the double carbonate is in the main one of recrystallisation, the ultimate result of dolomitisation is to produce a marble, and it is a fact that many of the coarsely crystalline marbles, such as that of Carrara and that of Port Shepstone,[1] in Natal, are dolomitic.

The pebbles of Carboniferous limestone compos-ing the Permian Brockram of the Appleby district have been extremely dolomitised subsequently to de-position ; in many cases the pebbles are reduced to a mere shell, usually lined with crystals of dolomite.[2]

The Replacement of Carbonate of Calcium by Carbonate of Iron.—A large quantity of iron goes into solution in the zone of weathering by the de-composition of the ferro-magnesian silicates of igneous rocks. The magnetite and ilmenite also of igneous rocks and the hæmatite and limonite of sedimentary rocks are attacked and dissolved by the action of the organic acids of the soil. Again, the sulphides of iron which, as iron pyrites, marcasite, pyrrhotite, and mispickel, are universally distributed through both igneous and sedimentary rocks, are oxidised by

[1] Hatch and Rastall, " Dedolomitisation in the Marble of Port Shepstone, Natal," *Quart. Journ. Geol. Soc.*, vol. lxvi, 1910, p. 507.

[2] Kendall, " The Brockram of the Vale of Eden," *Brit. Assoc. Rep.*, 1902, p. 604.

meteoric waters, and the iron removed in solution either as ferrous sulphate or as ferric sulphate, the former being the case where the oxidation has not been completed. The amount of iron derived from these various sources which is continually being removed from the zone of weathering is enormous: it has, for instance, been computed that there are, on the average, 13 tons of ferric oxide to a cubic mile of river water.

The portion of the iron-bearing solutions that penetrates to the zone of cementation produces, when it comes into contact with limestones, a metasomatic replacement by one of the following reactions :

(1) $FeSO_4 + CaCO_3 + 2H_2O = FeCO_3 + CaSO_4 . 2H_2O.$
(2) $2Fe_2(SO_4)_3 + 6CaCO_3 + 15H_2O = 6(CaSO_4 . 2H_2O)$
$+ 2Fe_2O_3 . 3H_2O + 6CO_2.$
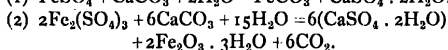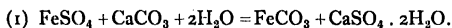
It will be seen that in the first case the carbonate of calcium is replaced by chalybite, and in the second by limonite, gypsum being a by-product in both cases. Metasomatic replacement of this character has produced valuable ironstone deposits in the Jurassic limestones of this country. There are three principal horizons that have been thus affected, viz. (1) the lower part (*scissum* zone) of the Northampton Sand, which forms the base of the Inferior Oolite. This ironstone is quarried in Rutlandshire (Cottesmore, Market Overton; and Uppingham), and in North-amptonshire (Corby, Desborough, Kettering, Thrapston, Wellingborough, Brixworth, and Towcester) ; (2) the Marlstone or *spinatus* zone of the Middle Lias,

which is mined in the Cleveland district of Yorkshire (Cleveland Main Seam) and quarried in South Lincolnshire (at Fulbeck, Caythorpe, Barkston, Honington, Woolsthorpe, Denton, and Harston), in Leicestershire (at Eaton, Eastwell, Stathern, Holwell, Wartnaby, and Tilton), in Northamptonshire (at Byfield and Hellidon), and in Oxfordshire (at Hook Norton, Adderbury, Milton, Astrop, Sydenham, Bloxham, and Wroxton); and (3) the *semicostatus* zone of the Lower Lias, which is quarried at Frodingham in North Lincolnshire.[1]

The Northampton ironstone was originally a sandy oolitic limestone which, by metasomatic replacement, has become a sandy oolitic ironstone. In the *Nerinæa* bed, which contains so many fossils of this horizon, the calcium carbonate of the shells is, as first pointed out by Sorby,[2] replaced by chalybite or limonite. When the shell is thick, as in the case of *Astarte*, an inner layer of calcite still remains unaltered.

The Marlstone is believed to have been originally a marly oolite which has been replaced, in the first place, by carbonate of iron.[3] The conversion of carbonate of calcium to carbonate of iron involves a diminution of volume which results in increased

[1] See Hatch, " The Jurassic Ironstones of the United Kingdom," *Journ. of the Iron and Steel Inst.*, 1918, p. 7. Lamplugh, Wedd, and Pringle, *Spec. Rep. Min. Res. Gt. Britain, Mem. Geol. Survey*, vol. xii, 1920.

[2] Sorby, " The Origin of Cleveland Ironstone," *Proc. Geol. Soc. West Riding*, 1856–57, p. 457, and *Quart. Journ. Geol. Soc.*, vol. xxxv, 1879, p. 85.

[3] Kendall, " The Iron Ores of the English Secondary Rocks," *North of England Inst. of Mining Engineers*, vol. xxxv, 1886, p. 113.

porosity, and thus furnishes the means for oxidation, so that by a secondary change limonite replaces the chalybite, especially near the surface. Greenish-grey cores of unaltered chalybite, however, often remain to tell the story.[1]

Of a somewhat different character is the metasomatism that has given rise to the enormously important hæmatite deposits of Cumberland and north Lancashire, as well as many others in different parts of the world. The iron ore appears as basin-shaped hollows on the upper surface of the Carboniferous limestone, or fills spaces of very variable and irregular form within the limestone or at its unconformable contact with the underlying Ordovician and Silurian rocks. There is no doubt that the iron ore has been formed by metasomatic replacement of the limestone, since large masses of hæmatite often contain a core of unaltered limestone and the characteristic fossils can sometimes still be traced in the ore. The iron seems to have been brought in by water percolating through the rocks above and along the impervious rocks below the unconformity, the dissolved iron compounds being perhaps derived from coal measures that once existed in the region and were removed by denudation.[2] The highly important iron ores of northern Spain (Bilbao, etc.) are of a similar origin, having been formed by the alteration of a limestone

[1] Hudleston, "The Geological History of Iron Ores," *Proc. Geol. Assoc.*, 1889, p. 104. Stead, *Proc. Cleveland Inst. Eng.*, 1910, p. 75.

[2] Bernard Smith, "Hæmatites of West Cumberland, Lancashire, and the Lake District," *Mem. Geol. Survey*, 1919.

of Cretaceous age, equivalent to the Gault of southern England.

Phosphatisation. — Limestones, mudstones, and shales which originally contained abundant fish remains, whether skeletal or excremental, or which have been penetrated by waters carrying phosphates leached from overlying guano beds, are often highly phosphatised by metasomatic replacement along certain zones or in isolated patches. Where the phosphate-bearing solutions attack limestones, calcium phosphates are produced ; where they attack argillaceous or igneous rocks, phosphates of aluminium or iron are formed, by chemical interchange of phosphoric for silicic acid.

Examples of limestones phosphatised by meteoric water are found on the islands of Sombrero, Mona, and Moneta[1] in the West Indies, and Teall, in describing a phosphatised trachyte from Clipperton Atoll, in the Northern Pacific, mentions that the coral rock of the same island is also phosphatised, both rocks having derived their phosphate in the form of an ammonium salt by leaching from guano.[2]

An excellent instance of the metasomatic replacement of calcium carbonate by calcium phosphate is described by Hayes[3] in the Carboniferous lime-

[1] D'Invilliers, *Bull. Geol. Soc. Amer.*, vol. ii, 1891, p. 75. Davidson, *Trans. Amer. Inst. Min. Engin.*, vol. xxi, 1892–93, p. 139. Julien, *Amer. Journ. Sci.*, 1863, p. 424. Shepherd, *Amer. Journ. Sci.*, 1882, p. 400.

[2] " A Phosphatised Trachyte from Clipperton Atoll," *Quart. Journ. Geol. Soc.*, vol. liv, 1898, p. 230.

[3] Hayes, *U.S. Geol. Surv., 17th Ann. Rep.*, 1895–96, p. 538.

stone of Tennessee. The so-called " white-bedded phosphate " or " sandy phosphate " of that State occurs in regular bands alternating with thinner beds of chert. Examination under the microscope shows that the phosphate is present partly as an isotropic material replacing rhombohedral crystals of calcite, partly as a granular aggregate without crystal form. The ground-mass of the rock consists of cryptocrystalline silica. Chemical analysis of the rock discloses the following composition :

SiO_2	.	.	.	.	49.43
$Ca_3P_2O_8$	.	.	.	.	33.00
$CaCO_3$	.	.	.	.	15.21
					97.64

Note.—Iron and alumina were not determined.

The calcium phosphate thus introduced was no doubt obtained by meteoric waters, carrying carbonic and other organic acids, from sediments in the zone of weathering in which it had been deposited from sea-water by the aid of organisms.

Certain zones in the Upper Chalk of southern England are locally (as at Taplow and Southeram) highly phosphatic, the phosphate being in part due to the abundant presence of fish-remains (excremental pellets, teeth and bone fragments), in part to the secondary phosphatisation of Foraminifera and prisms from the shells of *Inoceramus*, which, together with a white calcareous mud of organic origin (the so-called coccoliths, discoliths, and rhabdoliths), make

up the bulk of these Chalk zones.[1] Similar phos-
phatic deposits in the Upper Chalk occur at Doullens [2]
in France, and at Ciply in Belgium.[3] To the brown
grains in the Ciply Chalk the definite formula
$4CaO \cdot 2P_2O_5 \cdot SiO_2$ has been assigned, and the mineral
has been termed ciplyte.[4]

Phosphatised shale beds have been described in
the Ecca Series of Natal, in which the phosphate is
metasomatic, being derived from fish remains, frag-
ments of which are found in the interior of nodules.[5]

In many stratified rocks such phosphatic nodules
are abundant. They sometimes occur in layers or
scattered throughout the rock; but their most char-
acteristic manner of occurrence is in association with
unconformities. In the Gault and other clay forma-
tions of the South of England are found occasional
bands of nodules, which originally consisted of calcium
carbonate, but have been more or less completely con-
verted into phosphate by percolating solutions. One
of the best-known phosphatic deposits in this country
is the Cambridge Greensand. This consists of the
heavier constituents of the upper part of the Gault,

[1] Strahan, *Quart. Journ. Geol. Soc.*, vol. xlvii, 1891, p. 356,
and *ibid.*, vol. lii, 1896, p. 463.

[2] Lasne, *Bull. Soc. Geol. Fr.*, 3rd series, vol. xviii, 1890, p. 441.

[3] Cornet, *Quart. Journ. Geol. Soc.*, vol. xlii, p. 325 ; see also
Renard and Cornet, " Recherches micrographiques sur la nature
et l'origine des roches phosphatées," *Bull. Acad. Roy. Belg.*,
3rd série, vol. xxi, 1891, p. 126.

[4] Ortlieb, *Ann. Soc. Géol. du Nord*, vol. xvi, 1888–89, p. 270.

[5] Hutch, *Annals of the Natal Museum*, 1910, p. 227, and
Report on the Mines and Minerals of Natal, 1910, p. 103.

left behind while the finer and lighter portion was washed away by currents during a local uplift (which produced a slight unconformity between the Gault and the Chalk). The water at this time was rich in phosphate compounds, derived from the decay of organic matter, doubtless largely consisting of the

FIG. 31.—A QUARTZ PEBBLE IN THE WITWATERSRAND CON-
    GLOMERATE REPLACED BY PYRITES (Lancaster West Gold
    Mine, Witwatersrand).

    An example of pyritisation. Crossed nicols.   × 17.
                    (After R. B. Young.)

excrement of animals. The resulting pebble-bed, which is to be regarded as the basal conglomerate of the Chalk, contains nodules of two types: (a) *dark phosphate*, consisting almost entirely of rolled Gault fossils, with a high percentage of phosphoric acid— these were first phosphatised in the Gault, and again

during the formation of the Greensand; (*b*) *light phosphate*, also largely consisting of fossils, but of species belonging to the lowest zone of the Chalk, and therefore constituting the indigenous fauna of the bed—in these the percentage of phosphoric acid is considerably lower than in the dark variety. The matrix of the Greensand is a sandy marl, with much glauconite. At various horizons in the Lower Greensand are layers of nodules and rolled fossils, highly phosphatised, consisting for the most part of species derived from the Jurassic and Lower Cretaceous beds. The origin of these deposits, which were once of much commercial importance, is essentially the same as in the case of the Cambridge Greensand.

Phosphatic nodules, commonly accompanied by glauconite, are usual accompaniments of unconformities and local wash-outs among rocks of all ages; and from their manner of occurrence it is quite clear that they belong specially to the shallow-water facies of sedimentation, and that the phosphatisation goes on concurrently with the deposition of the material in its present situation.[1] A further concentration

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[1] Osmond Fisher, " On the Phosphate Nodules of the Cretaceous Rocks of Cambridgeshire," *Quart. Journ. Geol. Soc.*, vol. xxix, 1873, p. 52. Bonney, " On the Upper Greensand . . . of Cambridgeshire," *Proc. Geol. Assoc.*, vol. iii, p. 1. Keeping, *The Fossils . . . of the Neocomian Deposits of Upware . . .* (Sedgwick Essay), 1883. Rastall, " The Blea Wyke Beds and the Dogger in North-East Yorkshire," *Quart. Journ. Geol. Soc.*, vol. lxi, 1905, p. 441. Woodward, " On a Phosphatic Layer . . . in the Inferior Oolite of Skye," *Brit. Assoc. Rep.*, 1901, p. 635. Rhodes, " On the Occurrence of Phosphatic Nodules . . . in the Upper

takes place after elevation, in the case of the calcareous beds, by a process of leaching out of the carbonate of lime, the less soluble phosphate accumulating as an impure residual deposit.

Pyritisation.—The replacement of quartz by pyrites is characteristically exemplified in the auriferous con-

FIG. 32.—QUARTZITE PARTLY REPLACED BY PYRITES
(Rose Deep Gold Mine, Witwatersrand).

An example of pyritisation. × 17. (After R. B. Young.)

glomerates of the Witwatersrand, in the Transvaal. These conglomerates have been extensively cemented by silica ; but subsequently to such cementation both the quartz of the pebbles and that of the cement has

Carb. Limestone . . . of Yorkshire," *Brit. Assoc. Rep.*, 1901, p. 655. For a general treatise on the origin of phosphate deposits, with bibliography, see Penrose, *Bull. No.* 6, *United States Geol. Surv.*, 1888.

in many cases been replaced by pyrites [1] (Figs. 31 and 32). So complete is this replacement that pseudomorphs of pyrites after quartz pebbles have even been mistaken for " rolled pebbles " of pyrites.[2] The pyritisation of these conglomerates was accompanied by the precipitation of gold, this mineral being
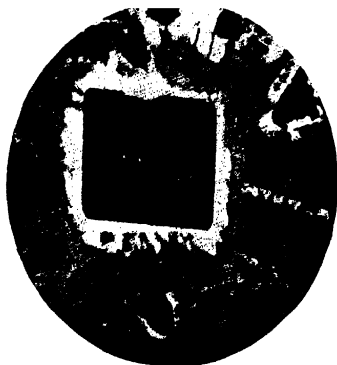
FIG. 33.—PYRITISED SLATE (Clanwilliam, Avoca, Wicklow).

The pyrites crystal is surrounded by a shell of chlorite.
Ordinary light.   × 15.

found in the most intimate mechanical association with the pyrites, either attached to individual crystals or in the interstices between the aggregated crystals.

Metasomatic Ore-deposits.—Important deposits of metallic ores of many kinds are frequently localised

[1] Young, *Trans. Geol. Soc. S. Africa*, vol. x, 1907, p. 24.
[2] Becker, 18th *Annual Report, U.S. Geol. Survey*, 1896–97, vol. v, p. 167.

at the contact of igneous rocks and calcareous sedi-
ments, and many of these have undoubtedly been
formed by an actual replacement of the limestone by
material derived directly from the igneous magma,
especially by magnetite, hæmatite, and sulphides.
Such ores are usually accompanied by recrystallised
calcite and a large variety of calcium, magnesium, and
iron silicates, partly derived from the magma and
partly from the originally impure calcareous and dolo-
mitic rocks.   Many of the most famous of the Swedish
iron-ore masses, such as the magnetites of Dannemora,
Norberg, Persberg, and those of Arendal in Norway,
occur as lenticles in highly metamorphic calcareous
rocks ; one particular type of diopside-garnet rock,
with or without epidote, known as " skarn," is highly
characteristic both of these deposits and of the sul-
phides.[1]   In other parts of Sweden important masses
of manganese ore occur in a similar way.   The sulphide
ores found in association with highly calcareous schists
and crystalline marbles are most commonly galena
and zinc-blende, though pyrites is also occasionally
found in considerable masses along with lime-silicates.
The contact-deposits of Pitkäranta in Finland are of
special interest.   Three beds of crystalline limestone
interbedded with gneisses and schists and meta-
morphosed by intrusive granite contain a consider-
able variety of ores, including magnetite, cassiterite,

[1] " The Iron-ore Deposits of the World," *Int. Geol. Congr.*
Stockholm, 1910, and Vogt, "Jernmalm og Jernverk," *Norges*
Geol. Undersökelse, 1918, p. 30.

chalcopyrite, pyrite, blende, galena, and native bis-
muth. The " skarn " type of contact rock is well
developed and the ore-masses are clearly due to replace-
ment of limestone and dolomite rock.[1]

The consolidated sediments may be arranged
according to the size of their detrital constituents
and the character of their cementation or meta-
somatism, as in the table on p. 230.

[1] Trüstedt, *Bull. Comm. Géol. Finlande*, vol. iv, 1907.

CLASSIFICATION OF THE CONSOLIDATED SEDIMENTS

CHARACTER OF CLASTIC CONSTITUENT.	WELDED ROCKS. *Consolidated by pressure alone with little or no cementation.*	CEMENTED AND METASOMATIC ROCKS.						
		Siliceous (Quartz or Colloid Silica).	*Calcareous* (Calcite or Dolomite).	*Ferruginous* (Chalybite, Hæmatite, or Limonite).	*Phosphatic* (Phosphorite).	*Barytic* (Barytes or Witherite).	*Gypseous* (Gypsum).	*Pyritic.*
Pebbles and Large Fragments.	SOFT CONGLO-MERATE. Ex.: The Bunter Pebble-bed.	HARD SILICEOUS CONGLOMERATE. Ex.: The Hertfordshire Pudding-stone.	CALCAREOUS CONGLOMERATE. Ex.: The Enon Conglomerate of S. Africa.	FERRUGINOUS CONGLOMERATE. Ex.: The Car-stone of the Lower Green-sand.	PHOSPHATIC CONGLOMERATE.	BARYTIC CONGLOMERATE.	GYPSEOUS BRECCIA. Ex.: The Brockram.	PYRITIC CONGLOMERATE. Ex.: The "Banket" of the Witwaters-rand, Transvaal.
Quartz Sand.	SOFT SAND-STONE. Ex.: The Midford Sand (Jurassic).	HARD SILICEOUS SANDSTONE. Ex.: The Stiper Stones.	CALCAREOUS SANDSTONE. Ex.: The Jurassic of the Isle of Eigg.	FERRUGINOUS SANDSTONE. Ex.: The Lower Greensand.	PHOSPHATIC SANDSTONE.	BARYTIC SANDSTONE. Ex.: Alderley Edge Sand-stone.	GYPSEOUS SANDSTONE. Ex.: The Sahara Sandstone.	PYRITIC SANDSTONE. Ex.: The Wit-watersrand Sandstone.
Argillaceous Mud and Clay.	SHALE and MUDSTONE. Ex.: The Upper Lias Shale.	JASPEROID. Ex.: Lake Superior.	CALCAREOUS SHALE.	BANDED IRON-STONE SHALE. Ex.: The "Calico" rock of S. Africa and Taconite of Lake Superior.	PHOSPHATIC SHALE. Ex.: Esca Shale (locally).	BARYTIC SHALE. Ex.: Carb. fire-clay of Seaton, Northumber-land.	GYPSEOUS CLAY AND SHALE.	PYRITIC SHALE. Ex.: Lower Palæozoic and Lias Shales.
Calcareous Ooze.	CHALK and SOFT LIMESTONE.	CHERT and NOVACULITE (Whetstone).	CRYSTALLINE LIMESTONE or DOLOMITE. Ex.: The Car-boniferous Limestone.	OOLITIC IRON-STONE. Ex.: The Cleve-land main seam.	PHOSPHATIC LIMESTONE. Ex.: Coral Lime-stone of Christmas I.			

CHAPTER III

CONTACT-METAMORPHISM

UNDER this heading may be included all the changes
set up in rocks by rise of temperature, unaccompanied
by any notable amount of differential movement and
reconstruction directly attributable to pressure. This
rise of temperature is connected with the intrusion
of igneous magma, the effects produced by lava
on the strata over which it flows being practically
negligible.

Factors influencing Contact-Metamorphism.—The
character and extent of the metamorphism produced
by any given intrusion depend on a large number of
variable factors, of which the following are the most
important: (1) the size of the intrusion; (2) its
temperature; (3) the rate of cooling; (4) the pressure
of the superincumbent rocks; (5) its petrographical
character; (6) the nature of the rock acted on.

Size of the Intrusion.—The size of intrusive masses
varies within very wide limits, and every possible
gradation exists between these limits. Consequently
no very precise nomenclature is possible; in practice,
however, certain types can be roughly distinguished,

e.g. dykes, sills, laccoliths, and bathyliths, the size of which may vary from a fraction of an inch to scores or even hundreds of miles. In the case of the larger bathyliths, however, it is still undecided whether they are to be regarded as wholly intrusive, or whether they were in part formed by the fusion and crystallisation *in situ* of pre-existing stratified rocks. There is no doubt that the hypabyssal and smaller plutonic intrusions have, at any rate, been injected in the molten state, and, other things being equal, the metamorphic effect of the larger is greater than that of the smaller.

Temperature of the Intrusion.—This is a factor that has an important bearing on the character and extent of the mineralogical and physical changes set up in the surrounding rocks. Three principles may be laid down : (1) greater changes are produced at a high than at a low temperature ; (2) at different temperatures the same chemical constituents may combine in different ways to form different minerals ; and (3) many crystalline minerals, when subjected to a change of temperature and pressure, are transformed to others having a different crystalline form and different physical properties. It follows that, at a given pressure, the mineralogical composition of an altered rock depends on the temperature to which it has been raised, and that this is controlled by the temperature and size of the intrusion, as well as by the initial temperature of the altered rock itself.

Rate of Cooling.—The rate of cooling of an in-

trusive mass and of the heated rocks surrounding
it is a function of several independent variables, of
which the most important are the size of the intrusion,
the conductivity of the rocks, and the thickness of
the cover. Since the effect of thermal metamorphism
is essentially to set the molecules in a state of more
active vibration, favouring fresh combinations, slow
cooling promotes the growth of large crystals, as in
the case of slowly-cooled igneous rocks ; consequently
a coarsely-crystalline structure in metamorphic rocks
may indicate both slow cooling and a high initial
temperature. A comparatively low temperature main-
tained for a long period may give rise to more con-
spicuous effects than a high temperature maintained
for a shorter time. Thus a small intrusion at a great
depth may be surrounded by a broad zone or aureole
of conspicuously altered rocks ; whereas a large mass
intruded near the surface may have produced com-
paratively slight alteration. Furthermore, if the sur-
rounding rock was already hot at the time of intrusion,
the amount of alteration may be out of all proportion
to the size of the igneous mass. For this reason in-
tense and far-reaching alteration sometimes surrounds
the pipes of volcanoes, which for a long time have
served as channels of escape for molten material.

   The Pressure.—In all cases of purely thermal meta-
morphism arising from igneous intrusion, without
any of the complications caused by extensive earth-
movements, the pressure is controlled primarily by
the thickness of the rock-cover at the time of intrusion.

Since some minerals possess two or more crystalline forms, each stable at a different pressure, the pressure determines, to a considerable extent, the mineralogical composition of the altered rock. High pressure favours the production of minerals of low molecular volume, or, in other words, of high density. Hence in metamorphism, as in all other physico-chemical processes, the effects of temperature and pressure are closely interwoven.

Petrographical Character of the Intrusion.—It is a matter of observation that the changes brought about in sedimentary rocks by the intrusion of acid rock differ both in kind and degree from those produced by basic material. This is due in part to the fact that acid intrusions are, as a rule, of greater volume than basic ones : we are acquainted with few basic intrusions comparable in size with the great bosses and bathyliths of granite ; so far as our present knowledge goes, basic magmas tend to form comparatively thin sheets and sills, or to occur in great masses of surface lavas, such as are produced by fissure-eruption. But this is probably not the sole explanation. The so-called *mineralising agents*, which play so important a rôle in contact-metamorphism, seem to be both more abundant and of a more active nature in relation to acid than to basic rocks, and in certain cases of granite intrusions the characteristic minerals of pneumatolysis are as much developed in the surrounding sediments as in the granite itself.

The Nature of the Rocks affected.—Sediments of

varying composition are susceptible to change in a very different degree ; and each sedimentary type, when metamorphosed, gives rise to a group of minerals whose composition depends both on the original chemical constitution of the rock and on the extent to which material from the magma has been added. It is evident, therefore, that each case must be treated on its own merits, and that no general rule can be formulated. Furthermore, under varying conditions of temperature and pressure, the same chemical constituents may group themselves to form different minerals or aggregates of minerals. Hence it is evident that according to the circumstances an endless variety of rock-types are possible ; this part of the subject will be treated more fully in later sections, when reference will be made to the original literature of each particular case.

The foregoing considerations make it evident that in studying contact-metamorphism an acquaintance with the conditions of formation and range of stability of the minerals produced is the first requisite. Given this, conclusions can usually be drawn as to the conditions under which the alteration took place in any individual case, and certain broad generalisations can be made. But it is impracticable to draw up for the metamorphic rocks a precise classification such as can be made for the igneous rocks. It is clear that metamorphism may vary in degree to an infinite extent, ranging from the very slightest alteration to a state of fusion so complete that the material becomes

for all practical purposes an igneous magma. This process merges into what is known as *assimilation*, by which term is understood the melting down and incorporation of sedimentary and other material by an invading igneous magma; and it is impossible to draw any definite line of demarcation between this and complete fusion.

Igneous magmas may be intruded into rocks of any kind, igneous, sedimentary, or metamorphic. Hence it is necessary to distinguish between the contact-metamorphism of igneous rocks, sedimentary rocks, and crystalline schists. The contact-metamorphism of the sedimentary rocks offers the most points of interest, and more attention has consequently been devoted to this branch of the subject.

Fusion of Sediments.—Comparatively little work has been done on the study of rocks believed to have been formed by the fusion and recrystallisation of sediments, and very few instances have been described in any detail. The phenomena produced vary greatly in character according to the scale on which the process has taken place, and it is hardly possible to give any account applicable to all cases.

In general terms it may be said that when the fusion of sediments has taken place on a large scale, and at a considerable depth, the resulting product resembles an igneous rock of intrusive nature, its petrographical character being controlled by the composition of the original sediment. Since most sedimentary rocks contain a high proportion of silica,

the recrystallised material generally tends towards the composition of a granite, or at any rate to that of an acid igneous rock : basic varieties seem to be much rarer. In such cases recrystallisation generally seems to have taken place under considerable pressure, with the production of well-developed parallel structure, and the rocks are best described as *gneisses*. A banded structure may also result from the preservation of the original stratification, especially when there is any conspicuous variation in the composition of different beds, such banded structures being characterised by the presence of layers of diverse mineralogical composition.

The question is, however, complicated by the possibility of movements of the fused material, analogous to the movements of intrusive magmas. These may lead to considerable disturbances of the surrounding strata ; the upward movement forcing up the overlying strata into a dome, and causing them to dip steeply away from the centre of the recrystallised mass. Such is the case with many of the great bathyliths of Laurentian gneiss in Canada.[1]

The conception of complete fusion was first put forward by Lawson [2] to explain the peculiar relations between the Archæan (Laurentian) and pre-Cambrian (Keewatin and Huronian) of the Rainy Lake region.

[1] See Coleman, *Presidential Address, Sect. C, British Association*, Sheffield, 1910, where the subject is treated in some detail.
[2] Lawson, " The Archæan Geology of the Region North-West of Lake Superior," *Congr. Géol. Internat.*, 1888, London ; *Comptes Rendus*, p. 130.

It was formerly supposed that the Pre-Cambrian sediments had been laid down on a floor composed of the denuded surface of ancient gneisses, just as the Torridon sandstone of Scotland rests on a denuded land-surface of Lewisian gneiss.   But along the margin of the Laurentian innumerable blocks of sedimentary rock are found enclosed in the gneiss.   These diminish in number away from the contact ; and the more distant from the boundary the more highly are they altered, until they can be traced into the darker patches and streaks of the gneiss.   Furthermore, veins and dykes of granitic material can be seen in many places penetrating the sediments, as in an ordinary intrusive contact.

The general structure of the Keewatin series at the time of the formation of the Laurentian gneisses appears to have been that of a geosynclinal.   The lower part of the series consisted of highly quartzose sediments,[1] while the upper part comprised a great thickness of volcanic rocks of a more basic nature. Owing to the continued depression of the geosynclinal, and the consequent piling up of a vast thickness of sedimentary and volcanic rocks, perhaps amounting to 50,000 feet, the temperature of the lower part was raised to such a point that the original rocks were fused, such fusion extending upward to a certain irregular line, which now forms the surface of division

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[1] For this lower quartzose division the name of Coutchiching series was employed by Lawson, but this term is now abandoned, and the whole is assigned to the Keewatin.

between the Laurentian and Keewatin series. This junction is naturally a very disturbed one, and partakes of the nature of a breccia on a very large scale. Eventually the temperature again decreased and the fused mass recrystallised : the lower quartzose division formed a highly acid granitic gneiss, with much quartz, whereas the more basic upper and marginal portion formed a syenitic or dioritic hornblende-gneiss, with little or no quartz.

A similar relationship has been established by Dawson [1] on Vancouver Island and on the adjoining mainland. Here the sedimentary rocks affected are much newer than in the region of the Great Lakes, being apparently of Triassic age ; fragments of them are similarly found to be included in the granitic gneiss near its margin.

On a much smaller scale than the foregoing, and of a very different character, is a case described by Clough and Harker. In the Isle of Soay, off the south coast of Skye, a very advanced degree of metamorphism has been produced by basic sills. Here the country-rock is a coarse grit of Torridonian age, consisting of quartz and alkali-felspar. At certain places the grit has been vitrified to a considerable extent by contact with sills, which are in no case more than 10 ft. thick. In its most altered condition the rock has the black vitreous appearance of a pitchstone ; but it contains

[1] Dawson, " A Geological Examination of the Northern Part of Vancouver Island," *Ann. Rep. Geol. Survey, Canada*, Report B, 1887, p. 11.

pale spots representing undestroyed grains of quartz. When examined under the microscope, relics of quartz grains are seen to be embedded in a matrix of colourless glass containing minute but well-formed crystals of magnetite, cordierite, and a greenish mineral which is perhaps aegirine. Some varieties contain, in addition, little rods of clear newly-formed felspar.[1]

This is a very remarkable instance of metamorphism, since there is no obvious reason why basic sills of so small a size should produce such widely-reaching effects, the influence of basic hypabyssal rocks being in general very small. It can only be suggested that the sills were intruded at an abnormally high temperature and under a thin cover of rock, under which conditions the cooling would be very rapid.

Metamorphism by Intrusion.—By far the most important division of the subject of contact-metamorphism is the study of the changes brought about in sedimentary rocks by the intrusion of igneous masses of varying size and composition, and the most satisfactory treatment of this part of the subject is founded on the lithological character of the sediments into which the igneous rock is intruded; for this purpose three general types may be conveniently distinguished, namely, the arenaceous, argillaceous, and calcareous.

The arenaceous and argillaceous groups differ more in structure and texture than in composition, their more important chemical constituents being

[1] " The Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey,* 1904, p. 245.

much the same in each case ; hence there is a general
similarity in the minerals produced in each. But the
chemical composition of the calcareous rocks is very dif-
ferent from that of the other two groups, and the contact
phenomena presented by them are of special interest.
In a few cases rocks belonging to other groups, such as
coal, have also undergone contact-metamorphism.

Contact-Metamorphism of Arenaceous Rocks.—In
the simplest case, namely, that of a rock consisting
solely of quartz grains cemented by silica, only one
chemical constituent is present and no reactions can
occur, the only possible change being recrystallisation.
When a sufficiently high temperature is attained, its
effect is to obliterate the distinction between the
clastic grains and the cement, producing an irregular
mosaic of quartz crystals without any regular outline,
but with crenulated edges closely interlocked as in the
sutures of the skull (Fig. 50). This constitutes the
typical quartzite. To the naked eye the rock presents
a finely granular or somewhat saccharoidal appearance.
In many cases the outline of the original grains can
still be made out, although the cement has become
thoroughly crystalline. But the sutured structure is
not peculiar to quartzites that have undergone contact-
metamorphism, and may be the result of cementation
at ordinary temperatures. For instance, it is quite
uncertain whether the Stiperstones which form the
basal bed of the Ordovician series of Shropshire have
undergone any contact-metamorphism.

Examples of the formation of quartzites by contact-

R

metamorphism are fairly abundant; but it is not always easy to say whether the alteration has been brought about by thermal or by dynamic agency, or by a combination of the two. Consequently the following have been selected as cases in which the thermal origin of the recrystallisation is undoubted,
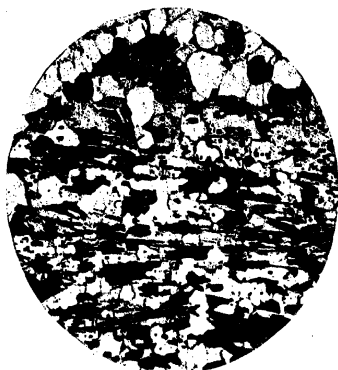
FIG. 34.—BANDED GRIT (highly metamorphosed in the granite contact-zone, Kentallen).

The dark part is biotite, the light part quartz and felspar. Ordinary light.   × 22.

owing to the close proximity of the quartzite to known intrusions. Pure quartzose rocks seem to be little susceptible to alteration; consequently the change does not extend very far from the intrusion. In the majority of cases, where the contact-metamorphism of arenaceous rocks has been described, the original sediments were highly impure; comparatively little

attention has been paid to the alteration of the purely siliceous rocks.

An interesting example of the metamorphism of a nearly pure siliceous rock is found in the Galloway district, where certain radiolarian cherts of Arenig age are altered by the Loch Doon granite.[1] The unaltered chert is a dark or nearly black rock, with white quartz veins. Under the microscope it is seen to be composed of clear crypto-crystalline silica, with rounded areas of somewhat coarser texture, representing the tests of Radiolaria. The interstitial part contains minute flakes of mica.

				I.	II.
Silica	.	.	.	91.3	93.3
Alumina	.	.	.	3.3	3.1
Ferric oxide	.	.	.	.7	.4
Ferrous oxide	.	.	1.4	.8
Lime	.	.	.	trace	.1
Magnesia	.	.	.	.8	.4
Soda	.	.	.	.2	.3
Potash	.	.	.	.6	.8
Loss	.	.	.	.9	.3
				99.2	99.5

I. Radiolarian Chert, Garryhorn Burn, near Carsphairn, outside the metamorphic aureole, anal. J. H. Player.

II. Coarsely crystalline quartz-rock, 1½ m. S.S.W. of Meaul, close to the granite, anal., J. H. Player.

As this rock is traced towards the granite it becomes light brown or grey in colour, and takes on the character

[1] *Annual Report of the Geological Survey of the United Kingdom*, 1896, p. 46. " The Silurian Rocks of Scotland," *Mem. Geol. Survey*, 1899, p. 640.

of a fine-grained quartzite. Close to the contact
the rock is often a coarse-grained aggregate of quartz,
having a brown colour and a peculiar resinous lustre.
The gradual increase in the coarseness of texture is
accompanied by the development of brown mica, at
first in minute scales, but in the final stages in flakes
with a diameter of .03 mm. to .05 mm. The resinous
appearance is due to the presence of minute inclusions
of biotite in the quartz. The rock is described by the
Geological Survey as a biotite-hornfels. The analyses
quoted on p. 243 show that there has been no appreci-
able alteration of composition, and the sole effect of
the granite is thus shown to be a molecular rearrange-
ment : the silica recrystallised as quartz ; while the
aluminous and other impurities formed biotite.

The alteration of the Armorican sandstone by
the granite of Guéméné, Brittany, has been described
by Barrois.[1] The unaltered rock is a grey sandstone
or grit, composed of more or less rounded quartz-
grains and flakes of white mica, embedded in a cement
consisting for the most part of white sericitic mica.
It contains a good many fossils of Arenig age. Barrois
divides the metamorphic aureole into three zones, as
follows (beginning with that most distant from the
granite) :

        1. Micaceous quartzite.

        2. Mica-sillimanite-quartzite.

        3. Felspathic mica-quartzite.

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[1] " Sur les grès métamorphiques du massif granitique du
Guéméné," *Ann. Soc. Géol. Nord*, vol. xi, 1884, p. 103.

The lowest stage of the alteration, the micaceous quartzite, consists of grains of quartz, often of very irregular outline, forming a mosaic, together with abundant dark mica, in flat, rounded, or hexagonal plates, showing pleochroic haloes around inclusions of zircon.

The rocks of the sillimanite-zone are distinguished from the preceding by the presence of minute needles of sillimanite in the quartz, as well as of crystals of sillimanite arranged in sheaves and bundles between the quartz grains. Part of the micaceous cement seems to have been converted into cordierite. This appears to be the most widespread form of alteration.

Close to the granite in some localities the rock contains, in addition to the minerals just described, abundant crystals of felspar, both orthoclase and plagioclase : it appears highly probable therefore that material has been transferred from the granite to the sedimentary rock.

The alteration of impure grits of Silurian age by the Galloway granites has been described by Bonney and Allport,[1] by Miss Gardiner,[2] and by the officers of the Geological Survey.[3] These grits contain a large proportion of argillaceous impurities, which have given rise especially to sillimanite and garnet. Miss

[1] Bonney and Allport, " Report on the Effects of Contact-Metamorphism exhibited by the Silurian Rocks near the town of New Galloway," *Proc. Roy. Soc.*, vol. xlix, 1889, p. 79.

[2] Miss Gardiner, " Contact Alteration near New Galloway," *Quart. Journ. Geol. Soc.*, vol. xlvi, 1890, p. 569.

[3] " The Silurian Rocks of Scotland," *Mem. Geol. Survey*, 1899, pp. 632-47.

Gardiner describes the changes that have taken place
in the sediments from zone to zone as the granite is
approached.   The grit passes into a coarsely-crystalline
gneissose rock, composed of quartz, two micas, garnet,
and sillimanite.   The first stage of alteration, according
to the Geological Survey, consists in the development

FIG. 35.—SILLIMANITE-GNEISS (from the granite contact-zone,
Knocknairling Hill, New Galloway).

Ordinary light.   × 16.

in the cement of small flakes of brown mica.   The
outlines of the grains of quartz and felspar are lost, and
the final product is a coarse-grained gneissose rock,
mainly composed of mica, quartz, sillimanite, and a
little felspar ; a good deal of red garnet is also present.
The sillimanite is specially abundant as needles in the
white mica (Figs. 35 and 36).

    One of the most important and interesting descrip-

tions of an area in which sedimentary rocks of arenace-
ous type have undergone a high degree of contact-
metamorphism is given in a paper by G. Barrow on
the rocks of the south-eastern Highlands.[1] The sedi-
mentary rocks were originally to a large extent of coarse
texture, though some bands were of argillaceous nature.

FIG. 36.—GARNET MICA-SCHIST (from the granite contact-zone,
Knocknairling Hill, New Galloway).

Crossed nicols.   × 13.

Pebbly grits when followed towards the intrusion
are seen to pass laterally into coarse gneisses. The
alteration is clearly progressive as the granite is
approached, and three clearly-marked zones are dis-
tinguishable, characterised by staurolite, kyanite, and
sillimanite respectively.

[1] Barrow, " On an Intrusion of Muscovite-biotite Gneiss in
the South-eastern Highlands of Scotland, and its accompanying
Metamorphism," *Quart. Journ. Geol. Soc.*, vol. xlix, 1893, p. 330.

The outer zone consists chiefly of a silvery-grey mica-schist with large yellow crystals of staurolite, which are often found, when examined under the microscope, to be replaced by the so-called " shimmer-aggregates " (patches of sericitic mica in minute flakes) ; some varieties also contain garnet. The ground-mass is made up of small crystals and flakes of white and brown mica and quartz. It seems probable that the original rocks of this zone were rather finer in texture than the rest, and of slightly different composition.

The middle or kyanite - zone consists largely of rather coarse - textured rocks, with large crystals of kyanite and flakes of brown and white mica in a gneissose matrix of quartz and felspar. Associated with these are schistose bands of a finer texture, also containing kyanite and doubtless derived from shales or mudstones. The rocks of the kyanite-zone can be seen to pass directly into the next type along their strike, and there is no doubt as to their derivation from the same material.

The sillimanite-zone consists of a grey gneissose rock containing quartz, felspar, muscovite, biotite, garnet, and sillimanite. The latter mineral exists in two distinct forms : (1) as small needles enclosed in quartz (the *quartz sillimanitisé* of French authors) ; (2) as bundles of fibrous crystals with frayed ends, squeezed between the other constituents of the rock. The felspar in this and other types is for the most part oligoclase ; and this is also the dominant felspar of the intrusions of this neighbourhood.

The direct passage, in approaching the intrusion, from rocks containing kyanite to those with sillimanite is thus dealt with by Barrow. It has been shown experimentally by Vernadsky [1] that when crystals of kyanite are heated to about 1380° C. at the ordinary pressure they are converted into sillimanite. Since the density of kyanite is higher than that of sillimanite (3.6 and 3.2 respectively) the temperature of transition would be raised by pressure ; hence the rocks of the innermost zone must in this case have been subjected to a temperature of at least 1380°, and perhaps considerably more. The nature of the minerals formed thus serves to a certain extent as a natural indicator of temperature, a geological thermometer.

The simple silicate of alumina, Al_2SiO_5, crystallises in three forms, viz. as andalusite, kyanite, and sillimanite. Unfortunately we do not as yet know the exact relationship between andalusite and kyanite ; but there cannot be much doubt that of the three, andalusite is the form stable at the lowest temperature, since it occurs abundantly in many metamorphic aureoles where we have reason to believe that a low grade of alteration has prevailed, and, moreover, this mineral is specially characteristic of the outer zones of many aureoles in Britain and elsewhere. On these grounds it might have been expected to occur in the outer zone of the aureole described by Barrow. Unfortunately it appears that the character of the original

[1] *Bull. Soc. Franç. Min.*, vol. xii, 1889, p. 447, and vol. xiii, 1890, p. 256.

rocks was not uniform over a sufficiently large area, and in the outer zone the characteristic mineral is staurolite instead of andalusite, probably owing to the presence of a larger proportion of magnesia and iron.

The metamorphic aureole of the Skiddaw granite is referred to in some detail under the heading of argillaceous rocks (see p. 254) ; but the alteration of the grey grits of the central belt[1] belongs here. Certain quartzose bands, especially free from impurities, have been converted into nearly pure fine-grained quartzites ; but where a considerable amount of detrital mica was present, cordierite and secondary brown mica have been formed. The progressive development of the former mineral can be followed as the intrusion is approached, and close to the granite small garnets are abundant. In other parts of the aureole large colourless prismatic crystals of andalusite are found embedded in a very dark or black ground-mass consisting of small grains of quartz and flakes of brown mica, with occasional cordierite.

From the foregoing descriptions it is clear that the principal result of contact-metamorphism on the ordinary type of arenaceous sediments is the formation of silicate minerals, and especially of silicates rich in alumina. Where the rock consisted entirely of silica, whether crystalline, as quartz, or colloid or crypto-crystalline, as in cherts, the whole recrystallises as quartz.

[1] Rastall, " The Skiddaw Granite and its Metamorphism," *Quart. Journ. Geol. Soc.*, vol. lxvi, 1910, p. 134 *et seq.*

Contact-Metamorphism of Argillaceous Rocks.—
The chemical composition of the argillaceous rocks
is very similar to that of the less pure members of
the arenaceous groups, the most notable difference
being a lower percentage of silica and a higher pro-
portion of alumina. Hence it follows that the lists of
minerals characteristic of each group are very similar :
in the argillaceous group the tendency towards the
formation of silicates containing alumina is even more
marked than in the arenaceous rocks, and such minerals
as andalusite (chiastolite), cordierite, and garnet are
specially characteristic (Fig. 37). Another notable
feature is the formation of spots, especially in the lower
grades of metamorphism ; that is, in the outer zones
of the aureoles. The nature of these spots will be
referred to later.

This type of metamorphism has been described
in much detail in many papers. There is a good
deal of variation in minor points ; but the general
principles involved are in most cases very similar. A
few well-known examples are selected for description.

A classical example of the metamorphism of
slaty rocks by a granite intrusion is that of the Steiger
Schiefer in Alsace - Lorraine, described by Rosen-
busch.[1] These rocks are typically argillaceous, and
may best be described as clay-slates. They have
undergone extensive alteration as a result of the

[1] Rosenbusch, " Die Steiger Schiefer und ihre Contact-zone
an den Granititen von Barr-Andlau und Hohwald," *Abh. zur
geol. Specialkarte von Elsass-Lothringen*, Strassburg, 1877.

intrusion of the large granite masses of Barr-Andlau and Hohwald; and since the composition of the sediments is fairly uniform throughout, it is possible to trace, with a considerable amount of accuracy, three concentric zones of progressive alteration, namely :

(1) *The Zone of Spotted Slate.*—On approaching
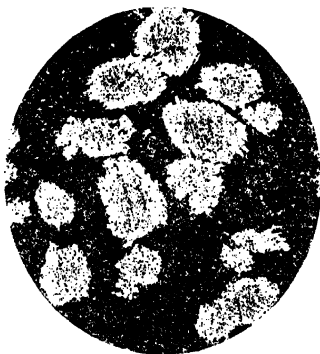
FIG. 37.—ANDALUSITE-BIOTITE ROCK (from the granite contact-zone, Haytor, Devonshire).

Ordinary light. (Photograph by Geol. Survey.)

the granite the first sign of alteration is the appearance on the surfaces of the slates of small dark spots, which appear to consist of accumulations of the black carbonaceous matter. There is little or no mineralogical change, and this type is called by Rosenbusch spotted slate with unaltered ground-mass (Fig. 38).

(2) *The Zone of Spotted Mica-schist.*—In the next zone the spots are still abundant; but the ground-

mass has also undergone recrystallisation, with forma-
tion of new minerals, especially mica and quartz, and
the cleavage has been obliterated. These rocks are
not true schists : the apparent schistosity is merely
a relic of the original bedding or cleavage and not
a secondary structure induced by pressure. Owing

FIG. 38.—KNOTENTHONSCHIEFER (Barr-Andlau, Vosges).
Ordinary light. × 12.

to the abundance of newly-formed mica, the rocks
have a distinctly crystalline appearance, and are best
described as spotted slates with crystalline ground-
mass.

(3) *The Zone of Andalusite - hornfels.* — Here the
structure has undergone a considerable change ;
cleavage and pseudo-schistosity have disappeared, and
the whole is converted into a fine-textured aggregate
of andalusite, mica, and quartz.

The most important general consideration that arises from a study of this area is that in all probability the rocks were not subjected to a very high temperature, since no kyanite or sillimanite has been developed. The facts rather point to the conclusion that the metamorphism was the consequence of the intrusion of a comparatively cool magma under deep - seated conditions ; in other words, the cooling was slow, and the changes, though not very strongly marked, extended for a considerable distance from the margin.

One of the best - known cases of contact - metamorphism in the British Isles is that of the Skiddaw granite, described in some detail by Clifton Ward in 1876. Ward recognised three zones, and summarised the results of his observations in the following words : [1] " On approaching the altered area the slate first becomes faintly spotty, the spots being of a somewhat oblong or oval form, and a few crystals of chiastolite appear. Then these crystals become more numerous, so as to entitle the rock to the name of chiastolite-slate. This passes into a harder, more thickly - bedded, foliated, and massive rock, spotted (or andalusite) schist ; and this again into mica-schist of a generally grey or brown colour and occurring immediately around the granite."

Recent researches [2] have shown that Ward's descriptions and conclusions need a considerable amount

[1] " The Geology of the Northern Part of the English Lake District," *Mem. Geol. Surv.*, 1876, p. 9.

[2] Rastall, " The Skiddaw Granite and its Metamorphism," *Quart. Journ. Geol. Soc.*, vol. lxvi, 1910, p. 134 *et seq.*

of modification. In the first place the succession described is founded on a traverse made across the strike of the rocks : when the various metamorphosed rock-types are followed along the strike, outside the boundary of the aureole, it is seen that there is much variation of composition. Consequently Ward's three zones do not refer to the same rock throughout. Secondly, the dominant mineral is not andalusite, but cordierite,[1] though andalusite is locally abundant.

The present state of our knowledge may be summarised as follows. The rocks of the Skiddavian series, into which the Skiddaw granite is intruded, include three principal rock-types. The main outcrop of the granite is wholly surrounded by grits, of which the alteration has already been briefly discussed (p. 250). On either side of the central grit-band is a belt of grey flags and fine gritty slates, rich in alumina, magnesia, and iron ; and in the southern belt a high grade of alteration is produced by the small granite apophysis of Sinen Gill. These form the spotted-schist and mica-schist of Ward. Outside of these again, on either side, is a belt of black carbonaceous slate, which on the northern and on the southern margin of the aureole is converted to chiastolite-slate. This belt is never seen within less than half a mile of the granite, from which it may be inferred that it has undergone only a small amount of metamorphism.

The black slate, when unaltered, consists of extremely minute grains of quartz and flakes of mica,

[1] Harker, *The Naturalist*, 1906, p. 121.

with a good deal of carbon, iron oxides, and pyrites, together with many small prisms of ottrelite. The first sign of alteration is the appearance of clear spots, which in some cases appear to be embryonic crystals of chiastolite, though perhaps more often they are merely due to a bleaching of the carbonaceous pigment, as in the Steiger Schiefer. In certain places chiastolite has begun to appear in rocks so little altered that well-preserved graptolites are still found in them. Almost the only change in microscopic structure is the development of a little more mica in addition to the crystals of chiastolite, although the latter are often also replaced by a micaceous or chloritic material.

The next belt consists for the most part of silvery grey flags or slates, consisting of minute flakes of mica, with grains of quartz and iron-ore. When altered these show a strong tendency to the development of spots, which in the majority of cases are more or less well-developed crystals of cordierite ; with increasing metamorphism much new mica is formed. Higher stages of alteration are found in the neighbourhood of the granite of Sinen Gill, and may be referred to two types. The less altered type is described as cordierite-gneiss ; it is a bluish-grey rock when fresh, consisting of cordierite, andalusite, and white and brown mica. Within a few feet of the contact the rock is much more micaceous, but the name mica-schist, applied by the older writers, is hardly applicable. A slight appearance of schistosity is simply due to the original bedding,

and the rock breaks more readily in any other direction. It consists almost exclusively of flakes of white and brown mica, with a little interstitial cordierite. Only within a few inches of the contact are small garnets and ragged patches of staurolite developed.

The dominant minerals throughout are cordierite and mica, especially brown mica. Muscovite becomes more abundant as the intrusion is approached. Andalusite occurs everywhere, but appears to be commoner in certain rather gritty bands. Garnet and staurolite occur only close to the granite. From these facts it may be concluded that no very high temperature was attained. The great size of the aureole—it has a diameter of over five miles, while that of the granite outcrop only measures one mile in its longest diameter—suggests the existence of a large granite laccolith, underlying the whole district at a comparatively small depth.

Contact - Metamorphism of Calcareous Rocks.— The contact - metamorphism of the calcareous rocks is a subject which has attracted much attention of late years, and many interesting investigations have been published. Since the chemical composition of this group of rocks is on the whole simpler and more definite than is the case in the groups hitherto dealt with, it is possible to establish certain principles applicable to the majority of cases hitherto examined.

A pure limestone consists of calcium carbonate, in the form of either calcite or aragonite, or perhaps sometimes in the amorphous state. When calcium

carbonate is heated with free access of air, it breaks
up into quicklime and carbon dioxide.   But it is
well known that if one of the products of this dis-
sociation is not removed, the action soon stops : in
other words, the reaction is a reversible one, and may
be represented by the equation

$$CaCO_3 \leftrightarrows CaO + CO_2.$$

Now, in the case of a deep-seated intrusion acting
on a limestone the carbon dioxide is not removed,
so that dissociation is prevented.   In consequence
the calcium carbonate simply undergoes crystallisa-
tion, always in the form of calcite, which is stable
under such conditions.   A pure limestone is therefore
converted by thermal metamorphism into a granular
aggregate of crystals of calcite, which commonly
show the characteristic lamellar twinning parallel
to the cleavages ; such a rock is known as *marble*
(Fig. 39).

Pure crystalline marbles are found in many parts
of the world, and some of them have long been famous
on account of their use for statuary purposes.   Many
of the best-known marbles of antiquity were formed
by metamorphism of limestones whose age is still a
matter of some dispute.   Examples are the marbles
of Carrara ; Pentelikon and Hymettus, near Athens ;
the island of Marmora, in the Sea of the same name.
Marbles are also found in many other regions, and
especially in the Archæan, as in Canada and the United
States, where beds of enormous thickness in the oldest

sedimentary series have undergone intense meta-
morphism.

When any other substance is present in addition to
calcium carbonate the action is no longer reversible,
and it is possible for a complete change to take place,
although the products are not removed. The simplest

FIG. 39.—CRYSTALLINE LIMESTONE, MARBLE
(Glen Tilt, Perthshire).
The individual grains of calcite show twin-lamellation.
Plane-polarised. × 11.

case is when the limestone contains silica as an im-
purity; the reaction may then be represented by the
following equation :

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2.$$
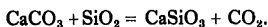
The lime-silicate thus formed is the mineral wol-
lastonite, and if sufficient silica is present the whole
of the rock may be converted into an aggregate of

crystals of wollastonite, which is commonly spoken of as *lime-silicate rock*. More commonly, however, the amount of silica is insufficient to decompose all the carbonate, some of which recrystallises as calcite, the rest forming wollastonite. This rock is known as *wollastonite-marble*.

Wollastonite - marble and lime - silicate rock are formed in certain cases where the Carboniferous limestone has been altered by intrusions, as, for example, in the neighbourhood of Carlingford, in Ireland. The Carboniferous limestone is commonly very free from aluminous impurities, but contains numerous bands and nodules of chert, which supply the silica necessary for the reaction in a readily available form.

When in addition to silica alumina is present, a much greater variety of minerals may be produced, according to the temperature and pressure attained. Among the more important new minerals are lime-garnet, idocrase (vesuvianite), and lime-felspar (anorthite). Of these the garnet is the commonest, and is probably formed at the lowest temperature. The formation of lime-felspar seems to require a high temperature. In the presence of a certain proportion of magnesia the chief mineral formed is diopside.

The metamorphism of the impure Coniston limestone by the Shap granite has been described by Messrs. Harker and Marr.[1] The limestone varies

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[1] Harker and Marr, "The Shap Granite," *Quart. Journ. Geol. Soc.*, vol. xlvii, 1891, p. 266.

considerably in composition. Some layers of nearly
pure calcium carbonate undergo simple recrystallisa-
tion as granular marble; but the greater part of the
rock, containing a good deal of silica and alumina,
gives rise to garnet, idocrase, and lime-felspar. Per-
haps the most interesting type of new product is a
rock composed for the most part of idocrase and

FIG. 40.—GARNET-IDOCRASE ROCK (from the granite
contact-zone, Shap, Westmorland).

Crossed nicols. × 14.

lime-garnet, with abundant minute granules of some
pyroxene (Fig. 40).

When magnesia is present pyroxenes are formed
abundantly, and in the more calcareous types much
wollastonite. Somewhat similar phenomena are shown
by some of the more calcareous beds in the suc-
ceeding Silurian rocks; in both cases the resulting

fine‑grained rocks may be described as *calc-silicate-hornfels*.

Dedolomitisation.—The effects of contact metamorphism on dolomite-rock may be summed up in the following way. According to modern ideas dolomite is a double carbonate of calcium and magnesium, having the formula $CaMg(CO_3)_2$: when this compound is heated it splits up according to the following equation :

$$CaMg(CO_3)_2 = CaCO_3 + MgO + CO_2.$$

This is not a reversible action, and the change can go on to completeness ; the resulting minerals are calcite and periclase. The latter is very hygroscopic, and in most cases soon combines with water to form brucite, $Mg(OH)_2$. The resulting rock is a mixture of calcite and brucite, known as *brucite-marble*. A rock of this composition has long been known in the Tirol, under the name of pencatite or predazzite, and was believed to be composed of a single mineral having the composition $CaCO_3 . Mg(OH)_2$. Microscopic examination has shown it to be an aggregate of calcite and brucite.

When the dolomite‑rock contains other substances as impurities, interesting combinations are produced, the minerals formed depending on the proportions in which the constituents are present. The most common impurity is silica ; when this is present in small quantity the following reaction occurs :

$$2CaMg(CO_3)_2 + SiO_2 = 2CaCO_3 + Mg_2SiO_4 + 2CO_2.$$
$$\quad \text{dolomite} \qquad\qquad \text{calcite} \quad \text{forsterite}$$
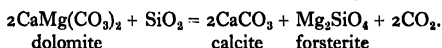
Forsterite is a member of the olivine group, and therefore liable to undergo decomposition to serpentine. When this mineral remains fresh the rock is called *forsterite-marble*, and when it is changed to serpentine the name *ophicalcite* is commonly applied to the green and white rock thus formed.

When excess of silica is present the reaction takes a different form, resulting in the production of pyroxene or amphibole, according to circumstances.

$$CaMg(CO_3)_2 + 2SiO_2 = CaMgSi_2O_6 + 2CO_2.$$
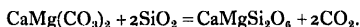
The ideal case may be represented as above, where the whole of the dolomite is converted to diopside. But as a rule dolomite-rock contains calcite as well as dolomite, and this may recrystallise along with the diopside, thus forming a *diopside-marble*. With great excess of silica, lime-silicate (wollastonite) would also be formed, giving thus a lime-silicate rock, composed of wollastonite and diopside.

The metamorphism of impure siliceous dolomite-rock has been studied by Dr. Teall in the Assynt district of Sutherland, and by Mr. Harker in Skye. The Durness limestone, of Cambrian age, which occurs in both these districts, is highly dolomitised; in places also it contains a good deal of secondary silica in the form of bands and nodules of chert. Where it is altered by the intrusion of members of the great plutonic complex of Loch Borolan it is converted for some distance into crystalline marble

(*e.g.* at Ledbeg), or into the various types of silicate rocks just described. To this process Dr. Teall has applied· the name of *dedolomitisation.*[1] The phenomena described by Mr. Harker in the neighbourhood of Kilchrist in Skye are quite similar. The ophicalcite - rocks in this neighbourhood often show a banded structure like that described as *Eozoon* in the Laurentian rocks of Canada, which was at one time supposed to be of organic origin.

It is clear, however, that the effect of thermal metamorphism on dolomite-rock is not always to decompose the dolomite into calcite and periclase, as described above ; under certain circumstances it can simply crystallise and form a *dolomite-marble.* In the southern part of Natal, along the Umzimkulu river, there is a great mass of coarse-grained, highly-crystalline, white marble, forming part of the old sediments of the Swaziland system, and metamorphosed by an enormous mass of granite, which surrounds it on all sides· and sends tongues and dykes into it. This marble has the composition of a dolomite with some calcite, as the following analysis shows :

Calcium carbonate	61.95
Magnesium carbonate	34.04
Ferrous carbonate	0.21
Insoluble matter	2.46
Water and loss	1.34
	100.00

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[1] " On Dedolomitisation," *Geol. Mag.*, 1903, p. 513; *Report Brit. Assoc.*, 1903, p. 660. " The Geological Structure of the North-West Highlands," *Mem. Geol. Survey*, 1907, p. 453.

It is probable that in this case both the temperature and pressure at which metamorphism occurred were very high, since the marble is very coarse in texture and is completely surrounded by an enormous mass of granite, extending over many hundreds of square miles. Under these circumstances it may be inferred
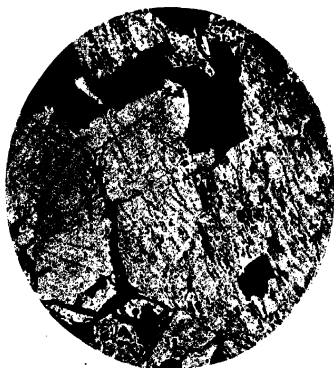
FIG. 41.—SCAPOLITE ROCK (Port Shepstone, Natal).

The scapolite is a dedolomitisation product.
Crossed nicols.   × 12.

that it was impossible for dissociation of the dolomite to occur.[1]

When alumina occurs in dolomite-rocks, either alone or in addition to silica, some interesting mineralogical changes take place. The simplest case is where alumina alone is present : this leads to the

[1] Hatch and Rastall, " Dedolomitisation in the Marble of Port Shepstone," *Quart. Journ. Geol. Soc.*, vol. lxvi, 1910, p. 507.

formation of spinel, as shown by the following equation :

$$CaMg(CO_3)_2 + Al_2O_3 = CaCO_3 + MgAl_2O_4 + CO_2.$$
$$\text{calcite} \qquad \text{spinel}$$
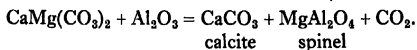
It appears to be very rare, however, for alumina to occur without some silica, and the most common

FIG. 42.—SPINEL-FORSTERITE ROCK (Port Shepstone. Natal).

The spinel (dark) and the forsterite (the mineral with numerous cleavage cracks) are both products of dedolomitisation. Ordinary light. × 12.

reaction results in the formation of spinel and forsterite; thus ;

$$3CaMg(CO_3)_2 + Al_2O_3 + SiO_2 = 3CaCO_3 + MgAl_2O_4 + Mg_2SiO_4$$
$$+ 3CO_2. \qquad\qquad \text{calcite} \qquad \text{spinel} \quad \text{forsterite}$$
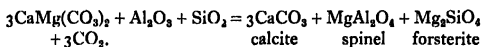
This association has been observed in the limestones of Glenelg in Inverness-shire,[1] and in an

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[1] Clough and Pollard, " On Spinel and Forsterite from the Glenelg Limestone," *Quart. Journ. Geol. Soc.*, vol. liv, 1899, p. 372.

impure portion of the dolomite-marble of the Um-
zimkulu River, Natal [1] (Fig. 42). It may be described
as *spinel-forsterite rock*, and in the latter case was
formed by interaction between the dolomite and
pebbles of a foreign rock enclosed in it. A similar
case is the formation of scapolite by the reaction with
pebbles of a felspathic rock (see Fig. 41).

Contact-Metamorphism of Coal.—In certain coal-
fields intrusions of igneous rock are not uncommon.
Their contact-effect is reciprocal, in some cases the
alteration of the intrusion being even greater than
that of the coal-seam. This special peculiarity is
due to the reducing action of the carbon of the coal,
which either prevents the formation of normal minerals
or destroys them shortly after formation. The coal-
fields of the central valley of Scotland afford an
interesting example of these phenomena. The Car-
boniferous strata of that district are intersected by
numerous dykes and sills of basic composition, norm-
ally appearing as dolerites. Where these intrusions
are in contact with coal-seams, they are found con-
verted to soft white or yellowish clay - like masses,
commonly known as " white trap."

Certain parts of the coalfields of Bengal are much
penetrated by dykes of a peculiar mica-peridotite, which
produce some striking effects both in the sandstones
and in the coal of the Damuda series. The dykes
must have been intruded at a very high temperature,
since the sandstones are partially vitrified and rendered

[1] Hatch and Rastall, *loc. cit.*

columnar in places. The effect on the coal is still more striking : although the dykes are only 4 or 5 feet thick, it is converted for a distance of 3 or 4 feet into columnar well-jointed coke, with films of igneous material between the columns. The percentage of volatile hydrocarbons is much reduced, with corresponding increase of the ash.[1]

Some of the coal-seams in the neighbourhood of Ladysmith have undergone alteration by thick dolerite sills of the Karroo series. Both the sandstones and the coal are much disturbed by the intrusions, forming a breccia consisting of small nodules and pellets of graphite in a white matrix ; while the sandstones for some distance away are changed to hard quartzite.[2] Instances are also known where most or all of the volatile constituents of the coal are driven off by the heat, the residue consisting of a soft sooty substance.

Metasomatic   Contact - Metamorphism. — In   the cases hitherto considered metamorphism has consisted solely of physical and mineralogical changes ; in other words, the elements present in the rock have merely entered into new combinations without affecting the bulk-composition. In the type of contact-alteration now to be dealt with, there is an addition of material, in some cases accompanied by the corresponding removal of other constituents, so that the

[1] Holland and Saise, " On the Igneous Rocks of the Giridih (Kurhurbaree) Coalfield and their Contact Effects," *Rec. Geol. Survey India*, vol. xxviii, 1895, p. 121.

[2] Hatch, *Report on the Mines and Mineral Resources of Natal,* 1910, p. 121.

metamorphosed rock differs in composition from the
unaltered material. Metasomatic processes of this
type are brought about by the action of the gases,
containing chemically active and often highly volatile
elements and compounds, that accompany or follow
the intrusion of plutonic masses. These gases are
most commonly a concomitant of granite invasions,
but are not unknown as accompaniments of more
basic intrusions. There is no doubt that they consist
of those constituents of the igneous magma that
possess the lowest freezing-points and that therefore
remain unsolidified long after the greater part of the
intrusion has become solid, or even comparatively
cool. Though highly volatile, their escape is pre-
vented at first by the pressure of the superincumbent
rocks, and what determines their final emission is
not quite clear. That this sometimes takes place
at a fairly late stage is shown by the fact that in
some cases rocks which previously had undergone
normal contact-metamorphism near the intrusion have
suffered further alteration by the addition of meta-
somatic constituents.

The agents that bring about changes of this class
are essentially the same as those that give rise to
the phenomena of pneumatolysis in igneous rocks.
They are, for the most part, substances of low atomic
or molecular weight, and are therefore very volatile.
The most important of them are superheated steam,
compounds of fluorine and boron, and, in a lesser
degree, compounds of lithium and beryllium : chlorine

probably plays a part also in connection with some basic intrusions; while many metallic elements accompany them and give rise to ore-deposits, which are often of great economic value. The secondary minerals resulting from these processes vary according to the composition of the rock acted on and the constitution of the gases themselves. Some of them are the same as those produced in igneous rocks, *e.g.* tourmaline, topaz, lithia-mica; while others, such as axinite and datolite, seem to be peculiar to the sediments, and especially to calcareous rocks.

These phenomena have been well studied in connection with the great granite-intrusions of Devon and Cornwall, where the processes of metasomatic alteration that have affected the surrounding sediments bear a close analogy to the pneumatolytic changes in the granites themselves. In the arenaceous and argillaceous rocks the most conspicuous new product is undoubtedly tourmaline, and in certain extreme cases it replaces almost everything except quartz, producing various types of tourmaline-schist, or even a rock very closely resembling the schorl-rock derived from granite. In all of these types fine needles of tourmaline show a very strong tendency to arrange themselves in stellate bundles. In less-advanced stages of alteration tourmaline occurs as a fairly common accessory together with andalusite, cordierite, and other minerals formed by normal contact-metamorphism.

In several localities gas-action of the type described

has affected impure calcareous bands in the Devonian and older rocks of Cornwall.[1] These phenomena have been studied in some detail in the aureoles of both the Land's End and the St. Austell granites, with very similar results. In most cases the characteristic mineral is axinite, together with smaller amounts of garnet, pyroxene, and amphibole, the latter mineral sometimes taking the form of asbestos. Tourmaline is rare in calcareous rocks, while fluorspar tends to occur in veins rather than as a constituent of the altered rocks themselves. Datolite, a somewhat rare boro-silicate of calcium, is sometimes formed in limestones.

[1] Barrow and Thomas, " On the Occurrence of Metamorphic Minerals in Calcareous Rocks in the Bodmin and Camelford Areas, Cornwall," *Min. Mag.*, vol. xv, 1908, pp. 113-23.

CHAPTER IV

REGIONAL METAMORPHISM

Factors influencing Regional Metamorphism.—The study of the extreme phases of metamorphism classed under the above head is hampered by exceptional difficulties. In the first place, it is often impossible to determine how much of the alteration is the result of purely mechanical pressure and how much is due to heat generated by friction during deformation. Certain it is that increase of pressure, even when unaccompanied by rise of temperature, is able to set up chemical and mineralogical changes in rocks ; and in some cases this cause may alone have been operative. But in most cases the metamorphism is more complex, and must be referred to several factors acting conjointly : the most important of these are (1) *heat*, whether due to the initial temperature or generated by friction, or dependent on chemical reactions ; (2) the presence or absence of *water*, or of substances dissolved in water ; (3) the *original structures* of the rocks affected, and especially the relation of planes of weakness to the direction of the pressure ; (4) the *chemical and mineralogical composition* of the original rock.

Another important factor is the *pressure* to which the rocks are subjected at the beginning of the process ; this is determined primarily by the *load*, by which is meant the weight of the superincumbent rock. The effects produced by a given lateral or tangential pressure will obviously be very different according as it acts on rocks situated in the zone of fracture or in the zone of flow. In the zone of fracture the pressure will largely find relief by faulting, thrusting, and folding, with their attendant friction and rise of temperature, whereas in the zone of flow there will be compression and chemical reactions or physical changes of an endothermic character.

Perhaps the most noteworthy feature of regional metamorphism is the great amount of alteration in the structures of the rocks affected. When this is accompanied, as frequently happens, by a partial or complete change in the mineral constituents, it is difficult, if not impossible, to determine the original character of the rock, or even to decide whether it was igneous or sedimentary. To take an example, the mineral composition of many felspathic sandstones, or arkoses, is almost identical with that of certain granites, from which they have been derived by denudation and deposition. During weathering the minerals undergo a certain amount of alteration, such as hydration ; but some of these processes are reversible, so that one of the effects of metamorphism is the tendency to restore the minerals to their original condition. Hence the rock resulting from the metamorphism

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of an arkose may closely resemble a rock of igneous origin. Such questions of origin can only be settled by tracing the same rock-mass through the various stages of alteration to its least altered representative, with which comparisons may then be instituted. Of late years the study of *progressive metamorphism* has been fruitful in valuable results, and has assisted in the solution of some complicated stratigraphical problems.

It would be foreign to the purpose of this book to discuss what is the ultimate cause of the movements of the earth's crust that have given rise to the phenomena of regional metamorphism. Suffice it to say that at certain periods in the geological history of the globe various regions have been subjected to intense crushing strains, usually in a tangential direction, and sometimes notably unsymmetrical or unilateral, with the result that portions of the crust have been transported for long distances along definite thrust-planes. Compression in one area was accompanied, in some cases, by corresponding tension in another; but on this point there is little certain information. The general effect on a large scale of such strains of compression is to produce crumpling, usually accompanied by dislocation and overthrusting; while on a small scale it manifests itself in the various phenomena of cleavage, foliation, shearing, etc., accompanied by molecular changes, of which the most important are recrystallisation of existing minerals and formation of new ones. In this way are formed innumerable new rock-types of

the most varied composition, but all having in common one character, namely, that they have suffered differential movement. As a collective name for all these rocks the term *crystalline schist* is universally employed. Although not free from objection, this name is a convenient one, and since it is now well understood, will be retained.

Even at the present day considerable divergence of opinion exists as to the respective parts played by heat, pressure, and chemical action in the formation of the crystalline schists. Some authorities ascribe almost the whole of the changes to pressure, others to the combined effects of heat and pressure ; while another school regards chemical action, and especially the action of solutions, as the determining factor. Since, however, the great depths at which the changes occur necessarily involve high pressures and high temperatures, and these in turn increase the chemical activity of solutions, it follows that all these causes must in general operate together. It is correct to say that the new structures are mainly due to pressure ; while the new minerals are the result of heat and chemical action, although the special crystalline form assumed by certain enantiotropic minerals is finally determined by the degree of pressure.

Structures due to Pressure.—The results of mechanical deformation are shown in their mildest form by the production of strain within the elastic limit, as when glass under compression or after sudden cooling becomes anisotropic. The strain-shadows, or

undulose extinction of quartz, is a precisely similar phenomenon. The formation of, and displacement along, gliding planes (as in calcite and kyanite), and the production of twinning by pressure (as in calcite and plagioclase felspar), are other examples. More advanced stages of deformation are represented by the flattening-out, elongation, and bending of pebbles, fossils, etc., and peripheral granulation, as in the so-called *mortar-structure* (*Mörtelstruktur*), with lateral displacement of the granulated material to lenticular and " *eyed* " forms (*phacoidal structure*). The *granulitic structure*, which is so characteristic of many of the finer-grained quartzose and felspathic gneisses and schists, is for the most part due to the same cause ; though no doubt actual formation of new minerals comes into play here, forming a transition to the next group. Complete granulation, or *kataclastic structure*, involving a mechanical breaking up and rearrangement of the constituents, with parallel orientation of constituents (cleavage, schistosity, foliation), is the last stage.

The terms *cleavage*, *schistosity*, and *foliation* are generally employed to describe the characteristic parallel structures produced by pressure, but the exact meaning of them is not very well defined. Cleavage and schistosity are generally restricted to rocks of fine and medium texture, whereas foliation is applied to the coarser types with conspicuous crystals or mineral-grains. Unfortunately, however, the term foliation has also been employed to describe

certain parallel structures in igneous rocks, that are simply due to flow of heterogeneous molten or partly crystallised magma (*primary gneissic banding*). In this sense no idea of fissility is necessarily implied. The foliation of dynamically metamorphosed rocks may also be described as *secondary gneissic banding*, since it is a structure superinduced in the rocks after their formation.[1]

The term *schistosity* is difficult to define precisely ; it may be taken to imply the presence in a crystalline rock of a parallel structure, either in one plane only or in several, in the latter case a crumpled or contorted structure being produced. A schist is not necessarily fissile, although in most of the rocks so described this property is more or less perfectly developed.

Cleavage, as applied to rocks, is the property of splitting to an indefinite extent into flat flakes of considerable extent, which are rigidly parallel and lie in one plane. The best example is afforded by ordinary roofing-slate, but less perfectly developed cleavage is very common in many fine-grained rocks.[2]

The nomenclature in common use for secondary structures may be summarised as follows : rocks of coarse texture, either non-fissile or splitting into thick slabs, are termed *gneisses*; rocks of medium texture, highly crystalline, generally fissile and often

[1] See Vol. I of this work, viz. *The Petrology of the Igneous Rocks*, p. 300.

[2] Harker, " On Slaty Cleavage and Allied Rock-Structures," *Rep. Brit. Assoc.*, 1885, pp. 836-41.

contorted, are known as *schists*; rocks of fine texture, well cleaved, if visibly crystalline, are *phyllites*; if not visibly crystalline are *slates*.

None of these terms, however, are very definite, and their usage varies much according to the predilection of individual writers.

Certain rocks do not readily assume parallel structures; for example, pure limestones, when crushed, tend to form granular marbles of homogeneous appearance. Owing to the softness of their components, the recrystallisation in this case is to be attributed to a high temperature induced by the pressure rather than to the pressure itself; and according to a well-known application of the law of reversible reactions chemical change is here excluded, just as in the case of thermal metamorphism of a limestone (see p. 257).

So far as the metamorphosed sediments are concerned, the groups of schistose rocks, as above delimited, correspond closely to original lithological differences. The pure argillaceous rocks give rise to slates and phyllites, or, if intensely altered, to certain highly micaceous schists. Impure clays and gritty shales are responsible for a great variety of schistose rocks, whose classification depends chiefly on mineralogical composition, although the resulting structures, especially crumpling and contortion, are also employed as distinguishing characters; the term *flag* is sometimes used for coarsely-cleaved, gritty varieties. The great group of the gneisses (excluding those of igneous origin) corresponds closely to the

sand and pebble deposits.[1] Even coarse boulder deposits are found among the crystalline rocks as sheared conglomerates, and various forms of phacoidal and eyed gneiss (Fig. 43).

One of the most noteworthy characteristics of rocks that have been subjected to intense pressure

FIG. 43.—FOLIATED PEBBLY GRIT (Zululand).
The pebbles crushed to lenticels. Ordinary light. × 13.

is the prevalence of parallel, banded, and lenticular structures.

The planes that determine these structures, whether or not actual or potential surfaces of discontinuity, are in most cases at right angles to the direction of maximum pressure ; but a banded

[1] The regional metamorphism of rocks consisting of quartz only gives rise to quartzites : since only one component is present, chemical reactions are excluded, and the whole recrystallises as a mosaic of quartz.

structure, consisting of elongated lenticular masses, may
be produced by combined faulting and crushing (*i.e.*
by a succession of small thrust-planes). In this case
shearing is dominant, and the resulting structural lines
lie more or less parallel to the direction of pressure,
or make only a small angle with it. Deviations from
the general parallelism of structural planes are also
due to the varying hardness in the different con-
stituents of the rocks affected. If these were originally
of coarse texture, such as conglomerates with finer-
grained interstitial matter, the surfaces of schistosity
or foliation wind round the larger and harder pebbles,
and produce thus a contorted structure. If the re-
crystallisation of both pebbles and matrix is complete,
a well-marked phacoidal or eyed structure is produced,
just as in the case of the metamorphism of porphyritic
igneous rocks (*Augen-gneiss*).

Cleavage.—The cleavage of metamorphic rocks
must be carefully distinguished from the cleavage of
minerals. It is unfortunate that this word is used
to designate two essentially different things ; for the
former is a secondary character, superinduced by
pressure, whereas the latter is a property inherent in
the mineral, and is in no way dependent on pressure.

It is doubtful to what extent cleavage can be
produced by a mere mechanical rearrangement of
rock - particles, without any accompanying minera-
logical change. Perhaps the simplest instance of
mere mechanical rearrangement is the secondary
lamination of certain shaly rocks by the weight of the

superincumbent strata. Fine-textured muddy rocks
appear to consist largely of minute flakes of mica
which may be supposed to lie at first in all positions,
but as the sediment accumulates and its weight in-
creases the mica-flakes tend to settle down with their
flat faces horizontal. Such a rock naturally splits

FIG. 44.—GRITTY SLATE WITH " FALSE CLEAVAGE "
(Isle of Man).

Manx slates. Ordinary light. × 11.

more readily along its bedding-planes than in any
other direction, since there is less interlocking of
the particles in those planes. This secondary shaly
structure is, in fact, a very simple form of cleavage.
It appears from the researches of Hutchings [1] that a
certain amount of mineralogical change does take
place, even in the apparently least altered argillaceous

[1] Hutchings, *Geol. Mag.*, 1890, p. 264, and 1896, p. 310.

sediments, and it may be even questioned whether
the mica in these shales is always original. For the
present purpose, however, this does not affect the
general argument. Certain cases of cleavage, as
exhibited by the Palæozoic slates, can probably be
explained on the same general principle of mechanical
rearrangement with a small amount of mineralogical
change ; except that here the pressure is not to be
referred to the weight of the overlying strata, but to
definite stresses of compression in the crust of the
earth, acting in the main in a tangential direction.
Since the bedding planes of undisturbed strata are
horizontal, it follows that the direction of cleavage,
being normal to the pressure, usually cuts the bedding
planes at a high angle ; in fact, it is only exceptionally,
as in the middle limbs of certain folds, that they can
coincide (see Fig. 45).

Cleavage is nearly always associated with strongly-
marked folding ; in fact, the cleavage of sedimentary
rocks does not begin, as a rule, till compression and
folding have reached their limit. Since the com-
pressibility of different rock-types varies very widely,
the combined folding and cleavage of heterogeneous
rock-masses produces some very curious and com-
plicated effects. It may be stated in general terms
that sandy and calcareous rocks do not undergo com-
pression to any appreciable extent, provided they
were already cemented or consolidated when the pres-
sure began to act, whereas argillaceous rocks, such
as clays, mud-stones, and shales, are very compressible

and cleave with readiness. Consequently, lateral pressure acting on a variable series of sediments produces folding and contortion in the harder bands; while the softer ones are compressed and cleaved,
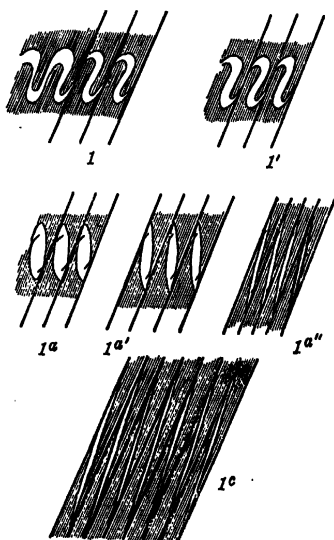
Fig. 45.—Folding and Cleavage in Devonian Rocks, Ilfracombe. (After Marr.)

perhaps without visible folding. For example, the Middle Devonian strata in the neighbourhood of Ilfracombe originally consisted of alternations of thin bands of limestone and 'grit with greater thicknesses of clay. These were affected by the pronounced post-

Carboniferous earth-movements of the Armorican series, and thrown into isoclinal folds, that are often overturned towards the north. The folding is very conspicuous in the limestone bands, but is scarcely seen in the intervening clays, which are converted into well-cleaved slates, the cleavage having a uniform dip : the relations of the two rock types are as seen in Fig. 45.[1] In the case of some thin hard bands the folding has been so intense that the middle limbs of the folds have been squeezed out altogether, and lenticular patches of limestone or grit have become isolated in the slates. In other instances thin grit-bands have been compressed and drawn out parallel to the cleavage, so that a sort of schistose structure is produced (see Fig. 45, 1ᶜ).

Where a great thickness of homogeneous rocks has been compressed, the cleavage is often extraordinarily perfect : some of the Welsh roofing slates can be split into laminæ thin enough to be flexible, and perfectly uniform slabs several feet square can be obtained. The homogeneity of many of the best Welsh slates, for example those of Ffestiniog in Merionethshire, is determined by the fact that they were deposited in the form of fine volcanic ash.

As already stated, there has been little change in the mineralogical constituents of many slates, but in others that have been subjected to a higher phase

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[1] Marr, " On some Effects of Pressure on the Devonian Sedimentary Rocks of North Devon," *Geol. Mag.*, 1888, p. 218. Bonney, *Pres. Add. Geol. Soc.*, 1886, pp. 97-8, and *Quart. Journ. Geol. Soc.*, vol. xl, 1884, p. 19.

of regional metamorphism the recrystallisation is complete. For such crystalline slates the term *phyllite* is employed. The dominant mineral of the phyllites is certainly some form of mica, either colourless muscovite or some brown or green variety (biotite or phlogopite). Minute crystals of andalusite, staurolite, garnet, etc., often occur, together with ottrelite and other minerals of the chlorite group, and even actinolite. The phyllites may often be conveniently described as micro-crystalline mica-schists; but there is no real line of demarcation between them and the true slates on the one hand and the mica-schists on the other. Phyllites are abundant in the older rock-formations, especially in the pre-Cambrian sediments and in regions of intense dynamic metamorphism of later rocks. In Britain they are common in the Dalradian series, and some of the Palæozoic rocks are most satisfactorily classified here, such as the Morte slates of Devon, while the phyllites or *phyllades* of Brittany and the Ardennes are well-known foreign examples.[1]

Strain-slip Cleavage.—When well-bedded rocks of fine texture are subjected to compression in a direction parallel to the lamination-planes they undergo folding on a minute scale, and when the pressure is distinctly unilateral it produces small asymmetric anticlines and synclines with the short steep limb on the side away from the pressure. Eventually fracture occurs along these steeper limbs, and a discontinuity,

[1] Renard, *Bull. Mus. Roy. Belg.*, vol. i, 1882, and vol. iii, 1884, p. 231.

either actual or potential, is brought about in direc-
tions nearly perpendicular to the pressure. This is
called *strain-slip cleavage* ; it differs from normal
cleavage in the fact that the rock can only be cleaved
into layers of a determinate thickness, whereas in
ordinary cleavage the subdivision of the laminæ may
be continued indefinitely. The phenomenon is

Fig. 46.—Puckered Phyllite (with folded bedding and strain-
slip cleavage parallel to the axes of the folds).

(Eilean Dubh, Argyllshire. Photograph by Geol. Survey.)

common also in slates and schists which have been
subjected to a second pressure in a direction making
a high angle with the original cleavage or lamination.
It often results in a peculiar minute wrinkling or
puckering of the surfaces, as in the roofing-slates
of Ballachulish or in the phyllites of Donegal, and,
on a larger scale, in the Devonian slates of Ilfracombe
and Morte Point in North Devon.

Schistosity and Foliation.—Under these names are included the parallel structures characteristic of rocks that have been subjected to a high degree of dynamic metamorphism, involving important mineralogical changes, and not unfrequently a complete reconstruction of the whole rock. There is no real line of demarcation between schistosity and foliation : they grade into one another, and for many rocks either term may be employed with almost equal correctness. Whereas the term cleavage is commonly restricted to rocks that can be split into flat slabs of considerable size, rocks which are properly designated schistose are usually much bent, crumpled, and contorted.

One of the most obvious characteristics of a large proportion of the rocks to which the term schist is most properly applied is the prevalence of mica in all its varieties ; perhaps the most typical of all is the fine silky-looking aggregate of minute mica-flakes which is generally called *sericite*. Many sericitic mica-schists approximate very closely to the phyllites described in the preceding section ; but their separation into laminæ is less regular and complete, and is generally along curved surfaces. The sericite is chiefly developed along the planes of schistosity, which may or may not coincide with bedding planes of the rock. A very common rock-type is the so-called quartz-schist, consisting of thin micaceous films separated by a varying thickness of quartz-grains ; it is, in fact, derived from a rock consisting of thin, sandy, and muddy layers, such as is being deposited

in many estuaries and shallow waters of the present day.[1]

Foliation may be defined as schistosity on a larger scale (the original flow-banding of igneous rocks, which is also sometimes called foliation, being of course excluded). As a rule, this term is applied when the rocks are coarser in texture and less markedly fissile. The foliated rocks often approximate very closely in appearance to igneous rocks. Their typical minerals are quartz and felspar, with mica and other minerals in subordinate amount; and the general name of gneiss may conveniently be employed for them.

Mylonitisation.—One of the most extreme phases of regional metamorphism is mylonitisation,[2] in which the pressure is so intense and is accompanied by such pronounced shearing strains that all original structures are destroyed. Without the consideration of transitional types it is impossible to determine the original character of a mylonite. Rocks of this type only occur in association with important planes of dislocation and differential movement, such as the great overthrusts of the north-west Highlands[3] and Scandinavia. Typical examples are found in the line of the great Moine thrust, where the process has affected rocks of varied origin. Mylonitisation is specially characteristic of the zone of fracture, in contradistinction to granulitisation, which takes place

[1] Barrow, *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 440.

[2] A term introduced by Lapworth in 1885.

[3] " The Geological Structure of the North-west Highlands of Scotland," *Mem. Geol. Survey*, 1907, pp. 597-8.

in the zone of flow; but the two types cannot be
sharply distinguished, since in heterogeneous rocks
different minerals may be differently affected, owing to
variations in hardness. Many of the mylonites as-
sociated with the Moine displacement are derived
from different members of the Lewisian gneiss; but
it is certain that some of the material involved in this
crush-zone was of sedimentary origin. In Eireboll,
Glencoul, and Assynt, the Cambrian quartzites, in
which the individual grains are scarcely visible, and
the epidote-grits and basal shales of the Torridonian
in the Kinlochewe district, have undergone similar
mylonitisation.

   Formation of Crush-conglomerates.—Crush-con-
glomerates connote rock-masses formed by the breaking
up into fragments of already solidified rocks under
the influence of earth movements, with subsequent
resolidification.[1] The simplest instance is afforded
by the belt of fragmental material which often marks
the line of a fault : these *fault-breccias* have often
suffered differential movement which so modifies the
original angularity of the fragments that a resemblance
to a clastic conglomerate is produced. The inter-
stitial spaces are at a later stage filled up by the deposi-
tion of cementing material, often in a crystalline form.
When the minerals thus deposited are ores valuable
deposits are often formed. When the two formations
thus brought into juxtaposition are of varying hardness

   [1] Van Hise, " Principles of North American Pre-Cambrian
Geology," 16*th Ann. Rep. U.S.G.S.*, part ii, 1896, pp. 679-83.

the result may be a rock composed of angular or
rounded fragments of the harder material embedded
in a paste or ground-mass of the softer. Such struc-
tures are common in the Algonkian of North America,
and an oft-quoted instance is in the Adirondacks,
where fragments of gneiss have been sheared off the
loops of sharp folds and embedded in limestone
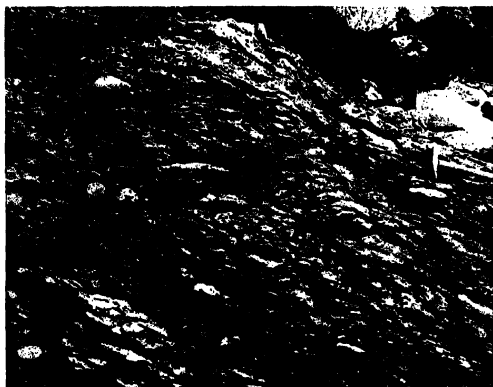
FIG. 47.—CRUSH-CONGLOMERATE (lenticels of gneiss in green
schist). (Glenelg, Inverness. Photograph by Geol. Survey.)

which, flowing under pressure, formed a matrix
enclosing the rounded blocks of gneiss.

In other instances a similar process over less
limited areas leads to the formation of broad zones
of shattered rock.[1] The crush-conglomerates of the

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[1] Lamplugh, *Quart. Journ. Geol. Soc.*, vol. li, 1895, p. 563,
and " The Geology of the Isle of Man," *Mem. Geol. Survey*, 1903,
p. 55.

Isle of Man include thick beds of imperfect con-
glomerates, containing irregular fragments of grit,
sandstone, and sandy slate, and less commonly of
smooth slate in a slaty matrix. Usually these have
a lenticular form. They vary in diameter from
several feet to almost microscopic dimensions, and all
sizes occur together. The harder fragments possess
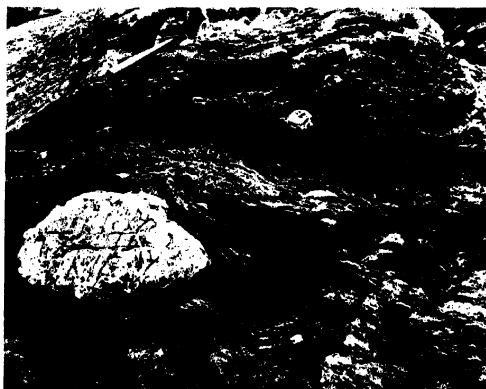
FIG. 48.—CRUSH-CONGLOMERATE (gneiss in green schist).
(Kirkton of Lochalsh, Ross.)

a sericitic skin due to shearing ; and shear planes also
traverse the matrix. Shatter-zones of this nature
are abundant in the north of the island, and cover a
large area, being conspicuous enough to be indicated
on the one-inch maps. Of similar character are the
great shatter-belts of the Lake District.[1]

[1] Marr, *Pres. Add. Geol. Soc.*, 1906, p. lxxvii.

Crush-breccias are, almost of necessity, formed from fairly hard rocks, and their component fragments are most commonly chert, quartzite, greywacke, hard slates, and cherty limestones or volcanic rocks.[1]

Effects of Pressure on Crystal Structure.—The phenomena just described are those affecting the structure of the rock as a whole ; but it is necessary also to take into account those that manifest themselves within the limits of a single crystal, often on a microscopic scale. These are due to a mechanical disturbance of molecular structure, and give rise to optical and other physical anomalies ; for example, it is not uncommon for minerals that are isotropic under normal conditions to become anisotropic as the result of pressure. · The simplest effect of strain is to disturb the regular orientation of the molecules : when the stress is removed, the mineral may recover its original properties ; but as a rule the effects of the pressure continue to manifest themselves. Perhaps the simplest case of all is the phenomenon of " strain-shadows," or undulose extinction, exhibited by quartz, and to a less degree by felspar. When a crystal, thus affected, is rotated between crossed nicols, the extinction is not sharp and uniform, but passes across the moving section in a wavy manner.

The lamellar twinning of minerals is also often greatly intensified by differential stresses. The twin-

[1] Lamplugh, " On some Effects of Earth-movement on the Carboniferous Volcanic Rocks of the Isle of Man," *Quart. Journ. Geol. Soc.*, vol. lvi, 1900, p. 11.

lamellæ, which always maintain the normal crystal-lographic orientation, tend to develop at points of extra strain, and are frequently localised along cracks and surfaces of discontinuity. With intensive stress the twin-planes pass over into actual discontinuities—the so-called " gliding-planes." These phenomena are common in plagioclase felspar, and still more so

FIG. 49.—CRUSHED MARBLE (Pyrenees).
Calcite with twin-lamellæ displaced by the crushing strain.
Crossed nicols. × 19.

in calcite. In both these cases the process is facilitated by the parallelism of the twin-planes to very perfect cleavages ; under shearing stresses minute faulting takes place along the cleavage planes, and this is specially noticeable in calcite, where two sets of twin-lamellæ and cleavages may be visible in the same section. A good example is shown in Fig. 49. Gliding-planes and the bending of crystal plates,

together with undulose extinction, are also well seen
in mica of various kinds. In all minerals possessing
good cleavages, the cracks are rendered more con-
spicuous by pressure ; and as the result of differential
movement, actual discontinuities are often produced
between the fragments. This, of course, graduates
eventually into kataclastic structure. In the case of
rocks possessing granulitic structure it is difficult,
and in some cases impossible, to determine whether
such structures are due to the fracture of pre-existing
mineral fragments or to new crystallisation.

Riecke's Principle.—The mechanical breaking
down of the minerals exposes a greater surface to
the influence of solutions, and thus promotes pro-
cesses tending to recrystallisation by solution and
reprecipitation. In the chemical changes that accom-
pany mechanical deformation, Riecke's principle is
of importance. This observer has shown that, *since
the solubility of a mineral is increased by pressure,
solution will take place at the points of greatest pressure
and recrystallisation at the points of relief.* A rock
under stress behaves as if it were plastic ; in reality
minute quantities of its constituents are dissolved,
transferred to another place, and reprecipitated. This
principle explains the high degree of development of
parallel structures in certain cases where the occur-
rence of very high pressures cannot be demonstrated ;
instances are on record where mica-schists and other
schistose and foliated rock-types appear to have been
formed by contact-metamorphism : although the

pressure was comparatively low, the high temperature and activity of solution effected a recrystallisation out of all proportion to the actual pressure.

The effects of high temperature and of high pressure on recrystallisation are in general antagonistic. Pressure, by increasing the solubility, tends to prevent crystallisation, whereas high temperature, by increasing the chemical activity and molecular movements, favours the formation of large crystals, especially if the heat is long maintained, just as slow cooling promotes coarse texture in the igneous rocks.

On the other hand Harker has drawn attention to the fact that shearing stress may invert the relative stability of two metastable dimorphous forms. Thus kyanite is a typical stress mineral, while andalusite belongs to rocks metamorphosed under no considerable shearing stress. Shearing stress favours the production of sericite and the chlorites, of albite among the felspars, of the epidote-zoisite groups, of amphiboles as opposed to pyroxenes, of kyanite and staurolite, chloritoid and talc, hæmatite and rutile. These may conveniently be termed stress minerals. On the other hand numerous minerals, such as anorthite, and the potash felspars, augite, forsterite, and andalusite, which are common products of thermal metamorphism, are scarcely produced under the influence of dynamic metamorphism, and may be distinguished as anti-stress minerals.[1]

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[1] Harker, *Proc. Geol. Soc.*, 1917-18, p. lxxvii. Grubenmann, *Die kristallinen Schiefer*, Berlin, 1904, p. 40.

Mineralogical Changes : Van't Hoff's Law.—Since rocks of any composition whatever, both sedimentary and igneous, may be subjected to dynamic metamorphism, it is evident that the mineralogical composition of the resulting rocks must vary greatly. We are here concerned only with the altered sediments, but these show a field of variation which is perhaps even wider than that of the igneous rocks.

The recrystallisation of rocks under pressure is dominated by the well-known law of Van't Hoff, which may be expressed as follows : *if a chemical system be compressed at a constant temperature, a displacement of equilibrium will take place in that direction which is associated with a diminution of volume :* in other words, minerals are produced that have a smaller specific volume than those from which they are formed. The minerals characteristic of this zone are therefore complex, stable, and of high density, and where there are two or more enantiotropic modifications of the same substance, that with the highest density has the preference ; thus titanium dioxide appears as rutile, not as brookite or anatase, and aluminium silicate as kyanite, not as andalusite or sillimanite.

The Part played by Water.—Although, as Spring [1] has shown experimentally, chemical reactions in which the new minerals are denser than the original

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[1] Spring, " Recherches sur la propriété que possèdent les corps solides de se soudre sous l'action de la pression," *Bull. Acad. Roy. des Sciences de Belgique*, vol. xlix, 1880, p. 322.

ones may be induced by pressure alone, in the vast majority of cases the reactions are controlled by the presence of water. Since, as a general rule, the volume of the solution is less than that of the solvent and the solute together, pressure increases solubility. Thus the solubility of the carbonates and silicates, which are the principal dissolved materials in underground solutions, is increased by pressure.

There can be no doubt that the effect of water is of the utmost importance in all kinds of metamorphism, and Arrhenius[1] has shown that superheated water under high pressures is a powerful chemical agent, capable of displacing silica from combination and thus of forming hydrates with the bases. When the temperature falls and the pressure decreases, silica again enters into combination with the bases ; but since the elements may group themselves in new combinations, the final products may be compounds differing from the original silicates. A process of this sort approximates very closely to actual fusion, and indeed, according to some authorities, igneous magmas are to be regarded merely as extreme cases of solution.

It follows that the solvent power of water on silicates and other minerals increases rapidly with the temperature and pressure. Thus apophyllite, which at normal temperatures is practically insoluble

[1] Arrhenius, " Zur Physik des Vulcanismus," *Geol. Fören. i Stockholm Förh.*, vol. xxii, 1900, p. 395. See also *Geol. Mag.*, 1907, p. 173.

in water, even under a pressure of 10 or 12 atmospheres
(Wöhler), is completely dissolved at a temperature of
180° to 190° C. According to Pfaff, quartz, which is
practically insoluble in pure water at normal pres-
sures, dissolves, under a pressure of 280 atmospheres,
to the extent of one part in 4700 parts of water in
four hours; while felspar submitted to a pressure of
100 atmospheres dissolves in three days to the extent
of one part in 3436 parts of water. However, the
" solution " of silicates under such conditions is to
be regarded as a process of hydrolysis rather than as
true solution.

The activity of aqueous solutions in bringing
about chemical interchange is considered to be largely
due to the dissociation or ionisation of the dissolved
substance. Thus a solution of sodium chloride con-
tains the free ions Na and Cl, and a solution of carbon
dioxide the ions H and HCO_3. To the presence
of these active ions is largely to be attributed the
profound influence of water in regional metamorphism.

Characteristic Chemical Changes.—The simplest
case which can occur in nature is that of a rock
consisting of pure silica, either crystalline or colloidal.
Since this constitutes a system of one component, it
is quite clear that no chemical reaction can occur,
and the only possible changes are physical. Since
quartz is the densest form of silica, all pure siliceous
rocks will recrystallise as quartz, forming quartzites :
original structures are destroyed, and the whole is
converted into a mosaic of clear formless crystals of

quartz, showing strain-shadows and other optical anomalies (Fig. 50). Very similar reasoning applies to the pure calcareous rocks ; according to the well-known law of mass action, the equation

$$CaO + CO_2 \rightleftarrows CaCO_3$$
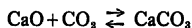
is reversible, and the only possible change under

FIG. 50.—QUARTZITE, with " crenulated " or " sutured " structure (Skye).

Quartz grains and siliceous cement both completely recrystallised to a mosaic of quartz. Crossed nicols. × 13.

conditions of high pressure is recrystallisation of the original calcium carbonate as calcite, forming marble. Dolomite also appears as marble under certain conditions (see p. 264).

The minerals formed from impure calcareous rocks are on the whole very similar to those produced by contact-metamorphism, with the important

exception that, instead of pyroxenes, amphiboles are formed, such as tremolite and actinolite. Since amphiboles possess a lower density than pyroxenes of the same composition, this is an exception to Van't Hoff's law, the reason for which has not yet been explained. The tremolite-marble of Glen Tilt in Perthshire is well known, and both this mineral and actinolite are abundant in many crystalline schists formed from impure limestones in other localities.[1]

The behaviour of the different varieties of felspar under the influence of metamorphism is a subject of much interest and importance. The potash felspars, orthoclase and microcline, generally recrystallise as such ; microcline is specially abundant in the flaggy gneisses of the Scotch Highlands, and orthoclase is common in almost all metamorphosed sediments, especially in those of somewhat coarse texture ; that is to say, it characterises the gneisses rather than the schists. But in the case of the plagioclase felspars the matter is more complicated. Stated in general terms, the soda-molecule and the lime-molecule behave differently : the soda-molecule readily recrystallises as albite, but the lime-molecule tends to form epidote, zoisite, garnet, and even chlorite. Hence lime-bearing plagioclases are rare in highly-altered rocks of schistose character. The general course of alteration of the plagioclase felspars has a close analogy to the processes of saussuritisation and albitisation in the basic igneous

[1] Adams, " On the Origin of the Amphibolites of the Laurentian Area of Canada," *Journ. of Geology*, vol. xvii, 1909, p. 1.

rocks. Hence albite is an exceedingly characteristic
mineral in altered sediments, especially in felspathic
sandstones, which ultimately form albite - gneiss;
while if the metamorphism is intense, the lime may
take part in the formation of some mineral of the mica
group, though more commonly it goes to form an
amphibole or epidote.

Under certain circumstances, however, the " pure "
potash and soda felspars (orthoclase, microcline, and
albite) undergo a different kind of alteration. Instead
of crystallising as felspar, they break up into mica and
quartz; since all mica appears to contain water, or at
any rate the OH group, as an essential constituent of
the molecule, it is probable that this change is brought
about by the action of highly-heated water : it may
therefore be regarded as a hydrothermal change,
analogous to the formation of greisen from granite.
The fact that quartz-mica-schists, such as are formed
from felspathic sandstones, generally show strongly-
developed parallel structures indicates that pressure
is an essential factor of the change.

The formation of micas of various kinds is perhaps
the most generally characteristic mineralogical change
in the metamorphism of mixed sediments, whether
by heat or by pressure, or by both acting together;
and water plays a considerable part in the process.
Besides the felspars, micas can be formed from a great
variety of other minerals, as well as from the finely-
divided muddy material of indefinite composition
that forms the base or paste of argillaceous rocks.

According to the chemical composition of the original rock, either colourless or brown mica (muscovite or biotite) may be dominant or both may occur together. The characters of sericitic mica are described elsewhere (see p. 287).

The pyroxenes recrystallise under pressure as amphiboles; this change, although more characteristic of the igneous rocks, may occur in sediments; chloritic and serpentinous material is generally converted into hornblende, and some chloritic and felspathic sandstones in the Dalradian series have been converted to hornblende schists, that are distinguishable only with difficulty from the typical hornblende schists produced from basic igneous rocks.

Rocks of the argillaceous group rich in alumina, magnesia, and lime give rise to aluminous silicates: andalusite, staurolite, kyanite, sillimanite, cordierite, and garnet. These minerals are the same as those formed by contact-metamorphism; but in the schists the most characteristic members of this group are kyanite and garnet. As already stated, kyanite has the highest density of the three enantiotropic forms of aluminium silicate, and it is therefore the most stable under high pressure. Andalusite, sillimanite, cordierite, and staurolite are found where the rocks have been subjected also to high, or comparatively high, temperatures. Garnets are exceedingly common in the schistose and gneissose rocks: garnetiferous mica-schist being one of the most widely distributed of all the ordinary rock-types (Fig. 51).

Glaucophane is not uncommon, but it is probably confined to schists derived from igneous rocks containing soda-lime felspar. Another silicate of the schistose group is scapolite [1] : this, however, is probably always formed by contact-metamorphism of calcareous sediments, or possibly in some cases from igneous rocks.
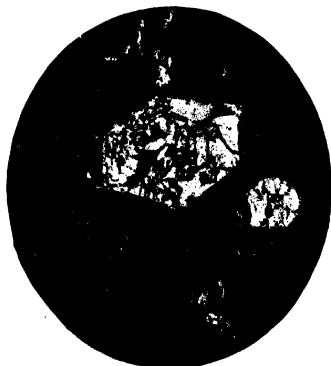
FIG. 51.—GARNET-MICA-SCHIST (Snaefell, Isle of Man).

Manx slates. Ordinary light. × 20.

Hence neither glaucophane nor scapolite properly belong to the present division of the subject.

Among the non-silicates a considerable variety of minerals are produced. The most important of these are the iron-ores, graphite, and the different forms of titanium dioxide.

When minerals of the iron-ore group are sub-

[1] Flett, " The Scapolite-bearing Rocks of Scotland," *Summ. Progr. Geol. Surv.*, 1906, pp. 116-31.

jected to regional metamorphism the resulting changes
tend in the direction of dehydration and reduction :
thus limonite and other hydrated oxides of the
sediments are converted into hæmatite or magnetite.
Both of these minerals are abundant in the crystalline
schists ; in many cases the iron compounds are believed
to have been introduced from above or below by
circulating waters, as in the case of the iron-bearing
schists of Michigan.[1] Magnetite - hæmatite - quartz -
slate is very abundant in the Swaziland system of
South Africa, in Natal and the Transvaal[2] ; similar
rocks also occur in the Griquatown series in the
northern part of Cape Colony. The rock very
commonly consists of thin alternating white or red and
black bands, and is called " calico-rock " by miners and
prospectors. The white bands are layers of very fine-
grained quartzite ; in the red varieties each grain
of quartz is covered by a layer of hæmatite, giving
a jaspery appearance ; the dark bands consist of
magnetite with some hæmatite and limonite. By
some authorities a rock of this kind is called jaspilite.
Some calico - rocks, as in Natal, contain hæmatite
rather than magnetite, but the difference is unim-
portant.[3]

The titanium of highly siliceous sediments forms

[1] Irving and Van Hise, " The Penokee Iron-bearing Series
of Michigan," *Monogr. U.S. Geol. Surv.*, vol. xix, 1892.

[2] Hatch and Corstorphine, *The Geology of South Africa*,
2nd edit., 1909, p. 100.

[3] Hatch, *Report on the Mines and Mineral Resources of
Natal*, 1910, pp. 67-70.

sphene, which is very common in felspathic gneisses, etc., but when the silica-content is low, this element appears as the dioxide TiO_2, which, as before mentioned, crystallises in three distinct forms, viz. rutile, brookite, and anatase. All three are found in metamorphic rocks ; but rutile, having the highest density, is the most stable and characterises the higher grades of regional metamorphism.

Many argillaceous sediments are rich in carbonaceous matter of organic origin, which in the zone of reduction and dehydration often gives rise to graphite, a common constituent of metamorphosed shales. The graphitic garnet-mica-schist of the Dalradian series is a well-known example. However, it is probable that deposits of graphite can also be formed in a purely inorganic way, namely, by the decomposition of metallic carbides derived from the heated interior of the earth. Some of the dyke-like masses of graphite in the older rocks have perhaps originated in this way, and the occurrence of graphite in a rock can no longer be accepted as a certain proof of the former existence in it of organic matter.

The Influence of Igneous Magmas. — Quite apart from the phenomena properly included under contact-metamorphism, certain aspects of the influence of igneous magmas on rocks undergoing regional metamorphism have to be taken into account. In the first place, igneous intrusions frequently accompany orogenic disturbances, assisting in the rise of temperature of the disturbed area and consequently in the

promotion of chemical activity. Again, in certain cases igneous magmas have undoubtedly supplied the heated water and other active agents that have given rise to much recrystallisation and formation of new minerals in crushed rocks.

But in many localities the process has gone further than this. Intrusion of igneous magma, commonly of an acid character, has taken place to such an extent just before or during the metamorphism of sediments by pressure that the sediments are literally permeated throughout by the igneous material, and it is impossible to decide whether the resulting rock should be regarded as of sedimentary or of igneous origin. In these cases the intrusion takes place chiefly along the dominant divisional planes, whether of bedding or of foliation. The whole phenomenon is commonly expressed by the term *lit-par-lit* injection ; [1] and it has undoubtedly been an important factor in the production of many types of banded gneiss.

The Crystalline Schists. — The origin of the crystalline schists for long remained an enigma to geologists, and from the early days of the science up to comparatively recent times many extravagant ideas have prevailed on the subject. However, these are now merely of historical interest, and it may be taken as established that the crystalline schists, using this term in its broadest sense, include representatives of both igneous and sedimentary rocks of the same

[1] Cole, " On Composite Gneisses in Boylagh, West Donegal," *Proc. Roy. Irish Acad.*, vol. xxiv, 1902–4, p. 203.

general character as those constituting the less altered portions of the earth's crust.[1] Transitional forms abound, and there can be no doubt that the rocks of this group, however abnormal they may appear to be, were formed by processes analogous to those now in operation. In the older rocks, now laid bare at the surface by denudation and upheaval, we see the results of processes that took effect at considerable depths, and it is only reasonable to suppose that similar changes are now progressing at depths inaccessible to direct observation.

The crystalline schists in the broadest sense of the term possess a very wide distribution—since, in fact, they underlie the stratified rocks in all parts of the world. Many of them, however, are clearly of igneous character, having been formed either by intrusion of igneous magma on a large scale, or by the fusion *in situ* of sediments. But it is equally clear that a large proportion have resulted from the metamorphism of rocks which were originally normal sediments, formed by the ordinary processes of denudation of older rocks and the deposition of the derived material. The greater part of these have resulted from the alteration of pre-Cambrian or Lower Palæozoic sediments ; but in some cases it is claimed that similar rock-types have been produced from Mesozoic or even from

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[1] " Études sur les schistes crystallins," *Congrès géol. internat.*, London, 1888. A collection of monographs summarising the state of knowledge at that date. A translation of these by Hatch was published in *Nature* for 1888. See also Grubenmann, *Die kristallinen Schiefer*, Berlin, 1904.

Tertiary rocks.[1] This view, however, is strongly combated by some of the foremost authorities, who maintain that the association of schists and post-Primary sediments can always be explained in some other way. In very many cases the age of certain masses of schistose rocks is still a highly controversial subject, *e.g.* in the Highlands of Scotland and in the Alps.

Since both temperature and pressure increase towards the earth's centre, the degree of metamorphism produced in any rock-group is a function of the greatest depth at which it has been buried at any period of its history, or in other words the amount of alteration depends on the greatest thickness of cover under which the rocks have lain. Now, in certain geosynclinal areas enormous thicknesses (in some cases up to 50,000 feet) of sediment have accumulated with little or no interruption. It is clear that the lower part of such an accumulation, and still more the rocks underlying it, must have been subjected to great heat and great pressure, tending toward strong metamorphism. Since geosynclinals are frequently upheaved to form mountain chains, with concomitant folding and fracture, it follows that the rocks forming the cores of folded mountain chains exhibit to a high degree the effects of these metamorphic processes. Some of the most striking examples of regional metamorphism are seen, for example, in the

[1] Walther, *Geschichte der Erde und des Lebens*, Leipzig, 1908, pp. 172-85.

heart of existing mountain regions, such as the Alpine chains, and in regions such as the Highlands of Scotland and Scandinavia, where mountain ranges of the Alpine type once existed.

It may be taken as now established that rocks of any age may be converted into crystalline schists, provided that they have once formed part of a geosynclinal. Such highly-altered rocks are less commonly exposed to view among the later formations than among those of earlier date, since the later rocks have had less chance of becoming deeply buried ; or, if so buried, they are less likely to have been again exposed. Also the lower rocks are naturally more altered than those above them. Consequently the crystalline schists form a dominant rock-type in the Archæan. They probably occur also to a considerable extent in the lower Palæozoic. Numerous Silurian fossils have been identified in mica-schists, and in calcareous concretions contained in them, as well as in marbles, in the neighbourhood of Bergen. These include such well-known and characteristic forms as *Favosites, Halysites, Cyathophyllum, Rastrites, Monograptus, Calymene, Phacops (Dalmanites), Encrinurus, Orthis, Stricklandinia,* etc.[1] Although not yet definitely proved, there cannot be much doubt that lower Palæozoic sediments have played a considerable part in the

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[1] Reusch, " Silurfossiler og pressede Konglomerater i Bergensskifrene," *Kristiania Universitetsprogram,* 1883 ; *Die fossilienführenden krystallinischen Schiefer von Bergen in Norwegen,* Leipzig, 1883. Kolderup, " The Geology of the Bergen District," *Proc. Geol. Assoc.,* vol. xxiii, 1912, pp. 19-21.

constitution of the gneissose and schistose rocks of
the Highlands of Scotland. Silurian and Devonian
fossils are also known to exist in the mica-schists of
Saxony. In the Taunus region in Germany [1] normal
Devonian slates, greywackes, and quartzites pass
laterally into rock-types, which are described as
crystalline schists, although the degree of meta-
morphism does not appear to be very high. Devonian
fossils have been recognised in crystalline rocks in
the Ardennes,[2] which are undoubtedly due to regional
metamorphism. In the Coast Ranges of California
there is a complete transition from normal unaltered
sediments containing Jurassic or Lower Cretaceous
fossils, *e.g. Aucella*, to massive crystalline and schistose
rocks with glaucophane, zoisite, garnet, and mica. In
northern California and in Oregon, shales and slates,
both above and below the Carboniferous Limestone,
can be traced into mica-schists and hornblende-
schists, and crystallisation can be seen in all stages.
Some of these are certainly of Mesozoic age.[3]

A clear and well-established case of the formation
of crystalline schists from sedimentary rocks is found
in the neighbourhood of the Lizard Point in Cornwall.[4]
The Old Lizard Head series consists of three well-
marked lithological types : mica - schist, granulite

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[1] Lossen, *Zeits. d. Deutschen Geol. Gesell.*, xix, 1867, p. 509.

[2] Gosselet, *Mém. Carte géol. France*, 1888, chap. xxv.

[3] Becker, *Bull. U.S. Geol. Survey*, No. 19, 1885. Whitney,
Geol. Survey, California, Geology, vol. i, pp. 23 and 225. Diller,
Bull. U.S. Geol. Survey, No. 33, 1886.

[4] Flett and Hill, " The Geology of the Lizard and Meneage,"
Mem. Geol. Survey, 1912, p. 33.

passing into gneiss, and green hornblende or chlorite
schist. All of these are cut by intrusions of granite,
gabbro, and serpentine, and have in places suffered
contact-metamorphism as well as crushing.

The mica - schists are reddish brown in colour,
coarsely crystalline, soft, and fissile ; they consist of
muscovite with a varying admixture of biotite with
small garnets and felspar ; quartz is not very common.
In places felspar is so abundant that it has formed
curious coarsely - crystalline patches or nests often
with quartz (segregation pegmatites).

The quartzofelspathic granulites contain in addi-
tion to quartz and felspar garnets, mica, and some-
times pale green hornblende. The felspars are
always completely recrystallised, and all epiclastic
structures are obliterated. Since these rocks are
much penetrated by veins of pink granite and aplite
it is often very difficult to distinguish between the
clastic and the igneous rocks, except by the microscope
or by chemical analysis.

The green schists rich in hornblende, chlorite, or
epidote undoubtedly represent beds of volcanic
material interstratified with the sediments, and meta-
morphosed with them.

Although intensely foliated, sheared, and folded,
the original stratification of the whole series is clearly
apparent, and chemical analyses likewise show that
the general composition of the first two groups is
inconsistent with an igneous origin. The high per-
centage of alumina and alkalies explains the presence

of abundant felspar, both orthoclase and soda-felspar in certain beds, and the mica-schist of Porthallow is clearly a typical argillaceous sediment which has undergone intense metamorphism.

So much controversy has arisen as to the age of certain schistose rocks in the Alps, variously claimed as of Palæozoic, Mesozoic, or even of Tertiary age, that no definite statement on the subject can yet be made. In certain cases the identification of schistose rocks as Jurassic was probably founded on mistaken identifications of supposed fossils; at the same time it is believed by the majority of geologists that the so-called "schistes lustrés," or Bündnerschiefer, include representatives of various Primary, Secondary, or lower Tertiary sedimentary strata. They include a great number of rock-types, some of which are crystalline, containing zoisite, garnet, felspar, and mica, in association with fossils, such as crinoids, belemnites, and lamellibranch shells. Associated with these more or less crystalline fossiliferous rocks are others in which no fossils have yet been found, but rich in such minerals as garnet, actinolite, staurolite, kyanite, biotite, and tourmaline. It is possible that the more highly-altered rocks are really much older than the others, and that two distinct series have been intimately folded together, producing a false appearance of continuity.[1]

The Metamorphism of Conglomerates. — One of the clearest proofs of the sedimentary origin of certain

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[1] Bonney, *The Building of the Alps*, London, 1912, pp. 56-70.

masses of schists and gneisses is the occurrence in them of pebble-beds and conglomerates still recognisable. as such. Every gradation can be traced from conglomerates in which the matrix or cement shows little or no alteration, through varying degrees of crushing and recrystallisation to the most extreme case, in which pebbles and matrix alike are rolled out flat, with twisting and contortion, to form streaky lenticular gneisses or schists.

A striking instance of the earliest stage of this process is the Polygenetic Conglomerate (Old Red Sandstone) of Cumberland.[1] This conglomerate consists of rounded and water-worn pebbles of a great variety of rocks embedded in a sandy matrix, the latter being only slightly consolidated, and easily removable by weathering. At a period subsequent to its formation, but previous to the deposition of the Carboniferous, this conglomerate was subjected to pressures arising from earth-movement. The matrix has remained almost unaffected, but the effect on the pebbles is striking. Owing to differential movement, some pebbles show scratches simulating ice-scoring; others are indented by the pressure of adjacent pebbles; sometimes complete impressions of small pebbles are shown on the surfaces of larger ones; pebbles of originally flat form are often cracked and bent; and, most striking of all, blocks of considerable size, up to 9 inches in diameter, are " faulted,"

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[1] Marr, " Note on a Conglomerate near Melmerby, Cumberland," *Quart. Journ. Geol. Soc.*, vol. lv, 1899, p. 11.

that is, fragments that have suffered differential move-
ment of an inch or so have been recemented.   Similar
phenomena are seen in the Old Red conglomerates
of Scotland and in the Enon conglomerates of Cape
Colony.   In these instances the disturbance doubt-
less occurred while the conglomerates were not deeply
buried, so that differential movement of the individual
pebbles could easily take place, and the fine matrix
was little affected.   But in other cases, where the
load was heavier, or, in other words, where the rocks
affected were in the zone of flow, the effects were of
a more far-reaching character.   Numerous instances are
known where the matrix has actually become schistose,
with complete reconstruction and recrystallisation,
while the pebbles have undergone various degrees
of deformation, depending partly on their original
hardness and partly on the intensity of the pressure.

The well-known Schichallion boulder-bed of the
Scotch Highlands occupies a definite horizon in what
is believed to be the upper part of the Dalradian
series, and it has been traced, with interruptions, from
Aberdeenshire to Islay.   In its most typical develop-
ment, as seen on the north face of the mountain
Schichallion in Perthshire, the matrix is usually a
dark to light grey, sometimes rather calcareous, mica-
schist, with abundant biotite.   The pebbles, ranging
in size from $\frac{1}{8}$ inch to 2 feet in diameter, are frequently
flattened and elongated.   The majority of them con-
sist of a grey or pink granitic rock, but there are also
present fragments of limestone and dolomite, grit,

quartzite, and quartz-schist, various kinds of mica-schist, actinolite-schist, and scapolite-gneiss.[1]

From its polygenetic character it is evident that this boulder-bed is a normal sedimentary conglomerate, formed by water-action during the deposition of the Dalradian series, and that it has been subjected to regional metamorphism, together with the rest of the series.

Similar instances of foliated conglomerates have been described from Sweden, Russia, Norway, and Saxony.[2] A fine example may be seen on the Dovre road in Norway, a few miles above Otta in the Gudbrandsdal. Here the pebbles, often over a foot in diameter, show signs of crushing, and recrystallisation has blurred their outlines. The matrix is a well-developed sericitic mica-schist.

The Obermittweida conglomerate, in Saxony, is an extreme case of the metamorphism of a pebble-bed.[3] Layers of sharply-defined and often well-rounded pebbles of gneiss, quartzite, and crystalline limestone are interbedded with fine-grained gneisses, greywacke, and mica-schists.

[1] " The Geology of the Country round Blair-Atholl, Pitlochry, and Aberfeldy" (Expl. sheet 55), *Mem. Geol. Survey, Scotland*, 1905, p. 60.

[2] Inostranzeff, *Studien über metamorphosierten Gesteine im Gouvernement Olonez*, Leipzig, 1879. Reusch, *Die fossilien-führenden Schiefer von Bergen* (German translation), Leipzig, 1883. Sauer, " Über die Konglomerate in der Glimmerschiefer-formation des sächs. Erzgebirges," *Zeits. für die ges. Natur-wissenschaft*, vol. lii, 1879.

[3] Sauer, *Erläuterungen zur Section Elterlein*, 2. Aufl., Leipzig, 1901, pp. 25 and 35.

Progressive Metamorphism.—The Highlands of Scotland is one of the best areas for the study of the progressive metamorphism of the sedimentary rocks.

In the north-west, from the neighbourhood of Cape Wrath to the southern extremity of the Isle of Skye, two principal periods of regional metamorphism have been established; the earlier of these is pre-Torridonian and correlative with the Huronian earth-movements of Bertrand;[1] while the later is post-Cambrian and was one of the principal manifestations of the Caledonian earth-movements. In the case of the earlier disturbances, which resulted from a pressure directed from N.E. to S.W., or *vice versa*, most of the rocks affected were of igneous origin, giving rise to the Lewisian gneisses; but associated with them in certain localities, as for example near Loch Maree, are schistose rocks, which are believed to represent original sediments and may possibly have formed part of a great sedimentary series of enormous antiquity, into which the plutonic rocks were intruded. They include mica-schists, graphite-schists, quartz-schists, siliceous granulites, limestones, dolomites, and cipolins.[2] The sedimentary origin of such an assemblage can hardly be doubted, and is confirmed by the existence in small quantity of kyanite-gneiss, the mineral kyanite being especially characteristic of highly-metamorphosed argillaceous rocks.

[1] Bertrand, " La distribution des roches éruptives en Europe," *Bull. Soc. Géol. France*, vol. xvi, 1888, p. 573.

[2] " The Geological Structure of the North-West Highlands of Scotland," *Mem. Geol. Survey*, 1907, p. 75.

Dr. Peach suggests that the graphite, limestone, and chert were probably accumulated from the remains of plankton, but this assemblage has been so completely altered that all traces of original organic structure in them has been destroyed.[1]

Almost the whole of Scotland to the north of a line drawn from the mouth of the Clyde to Stonehaven is occupied by a great rock series, consisting mainly of schists, but also comprising quartzites, limestones, and other types. Precisely similar rocks are found in the north of Ireland along the same line of strike. There is little doubt that the two districts were once continuous ; and, moreover, it is probable that at one time the northern part of the British Isles and the Scandinavian peninsula formed a single area of almost uniform structure and composition. The age of the series is still a matter of uncertainty : in all probability it includes rock-masses of very different dates, ranging from Archæan through Torridonian to Cambrian, and possibly even to later ages. In certain parts of the north-west Highlands, inliers of Lewisian gneiss have been recognised above great thrust-planes, which in places have carried masses of gneiss and schist for many miles over the Torridonian and Cambrian sediments.[2]

The Highland schists are generally considered to include two distinct portions—the eastern or Moine

[1] *Pres. Address to Section C, Brit. Asso:.,* Dundee, 1912.
[2] For a complete account of the structure and relations of these overthrust masses, see " The Geological Structure of the North-West Highlands," *Mem. Geol. Survey*, 1907.

schists, and the schists of the Central Highlands, that
lie mainly to the south of these ; but similar rock-
types are found in both areas, and they are probably
of common origin.   The Moine schists include four
principal types : (1) mylonised rocks ; (2) phyllitic
schists, siliceous schists, and limestones ; (3) granulitic
quartz-felspar-schists (Moine schists), with thin bands

FIG. 52.—BIOTITE GRANULITE (Moine gneiss).

(Dalnacardoch, Perthshire.   Photograph by Geol. Survey.)

of garnet-mica-schist ; (4) inliers of micaceous and
hornblendic gneiss.

The last group is of igneous origin and forms part
of the Lewisian gneiss ; but the others are undoubted
sediments.   Most abundant and characteristic of all
is the third group, generally spoken of as the Moine
schists.   Under the microscope a typical specimen is
seen to consist, in the main, of a microgranulitic

aggregate of quartz and alkali-felspar, in which flakes of mica are embedded. The grains of quartz and felspar are of approximately uniform size and shape, and the mica flakes do not merely lie between the constituents of the aggregate, but are included in them, so that a single flake of mica may pierce one
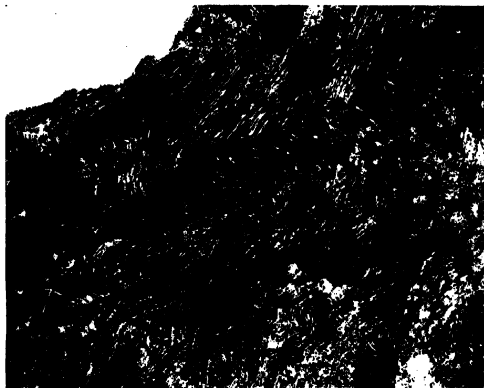
FIG. 53.— CONTORTED MICA-SCHIST (Arran).

(Photograph by Geol. Survey.)

or more contiguous grains. A rock of this character presents no trace either of epiclastic or of kataclastic structure ; it is a typical holocrystalline schist, produced by complete reconstruction and recrystallisation of the original rock under intense pressure.[1]

Schistose rocks of the Moine type cover a large

[1] *Op. cit. supra*, pp. 596-600.

extent of country in Sutherland, Ross, and Cromarty,
and extend for some distance south-east of the Cale-
donian Canal ; but in the central and southern High-
lands they are replaced for the most part by rocks
of the Dalradian type.   Certain areas of " Moine "
schists and gneisses have been identified in Aberdeen
and Perthshire ; according to Mr. Barrow, however,

FIG. 54.—MUSCOVITE-BIOTITE GNEISS (Moine gneiss).

(Perthshire. Photograph by Geol. Survey.)

the Moine gneisses of this region really consist of the
metamorphosed border of the Highland quartzite.[1]

The Dalradian series of the central and southern
Highlands consists, apart from igneous intrusions of
varying date, of a great mass of schistose rocks that
are undoubtedly of sedimentary origin.   The amount

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[1] Barrow, " On the Moine Gneisses of the East-Central High-
lands," *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 400.

of regional metamorphism that has affected them varies greatly in different places, and in many instances it has been found possible to trace a complete transition from almost unaltered clastic sediments to highly-crystalline schists and gneisses. The order of succession of the different rock-types has been worked out in much detail by the officers of the Geological Survey ; but it is still uncertain which is the base and which the top of the series, since there are many cases of undoubted inversion. The relation of the Dalradian schists to the Moine series is also uncertain, but it may be an unconformable one.

The Dalradian series comprises a great variety of rocks—mica-schist, quartz-schist, chlorite-schist, quartzite, conglomerate, and limestone ; they are much folded and foliated, and, as a rule, possess a very strongly-marked flaggy appearance, suggesting stratification, in most cases the superinduced schistosity being probably parallel to the original bedding-planes. Basic sills intruded along the bedding-planes are common ; they have been, for the most part, folded and foliated with the sediments in which they lie, and converted to epidiorite, hornblende-schist, or, in extreme cases, to chlorite-schist. Around many granite-masses of both older and younger age, the rocks present the characteristic phenomena of contact-metamorphism, and in some cases they are much interpenetrated by veins, dykes, and sheets of igneous material, with resulting complexity of structure.

According to the publications of the Geological

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Survey, the generalised succession of the Highland schists is as follows : [1]

> The Highland quartzite and pebbly conglomerate.
> Schichallion boulder-bed.
> Blair-Atholl limestone.
> Graphitic schist.
> Ben Lawers schist = Ardrishaig phyllite.
> Garnetiferous mica-schist.
> Loch Tay limestone.
> Garnetiferous mica-schist of Pitlochry.
> Green beds.
> Ben Ledi grits and schists.
> Aberfoyle slates.
> Leny grits.

The relation of this series to the Moine schists and gneisses is not known with certainty ; but since Moine rocks have been found in contact with different members of the above series, they are probably separated by an unconformity, and it is generally believed that the Moine series, as a whole, is younger than the schists of the central and southern Highlands. Some authorities, however, hold that the Moine gneisses should be placed below the Blair-Atholl limestone (see p. 320).

The metamorphism of these rocks is most intense in the central Highlands, in Perthshire and Aberdeenshire, decreasing towards the south-west. In the neighbourhood of Loch Awe and Loch Fyne the beds

[1] The above list has been compiled from various sources, especially from the *Memoirs of the Geological Survey*. For details, reference may be made to the Memoirs on Blair-Atholl, etc. (Sheet 55), Mid-Argyll (Sheet 37), the Geology of Cowal, etc. Gregory, *Handbuch der regionalen Geologie*, vol. iii, pt. i, p. 37.

above the Ardrishaig phyllites, including the repre-
sentatives of the Blair-Atholl limestone, have been
followed along the strike into rocks that are scarcely
more altered than many Palæozoic sediments.[1] They
are much folded, but not recrystallised, and it was at
one time believed that they must be newer than the
Dalradian rocks of Perthshire; but the evidence of
continuity and progressive metamorphism is quite con-
clusive. The presence of the well-known Schichallion
boulder-bed is alone sufficient proof.[2]

Other examples of progressive metamorphism
have been described from the neighbourhood of
Loch Lomond,[3] and from the region between the
River Garry and Balmoral.[4] In the Loch Lomond
district the Leny grits consist of a pebbly aggregate
of quartz and felspar, mostly oligoclase, embedded in
a fine matrix containing much chlorite, and partaking
more of the nature of a clastic than of a crystalline
rock, although it is slightly schistose. The Ben Ledi
grits are more granulitised, but on the whole are
very similar. The intervening Aberfoyle slates are
somewhat crystalline and phyllitic. Under the influ-
ence of increasing metamorphism the felspathic grits
undergo progressive recrystallisation, the most extreme

[1] Hill, " On the Progressive Metamorphism of some Dalradian
Sediments in the Region of Loch Awe," *Quart. Journ. Geol. Soc.*,
vol. lxv, 1899, p. 470.
[2] For an account of this bed, see p. 314.
[3] Cunningham-Craig, " Metamorphism in the Loch Lomond
District," *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 10.
[4] Barrow, " On the Moine Gneisses of the East-Central High-
lands," *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 400.

phase of alteration being the formation of coarse-grained albite-gneisses. These rocks consist of a granulitic aggregate of quartz, albite, and muscovite, with chlorite, magnetite, and epidote, the latter mineral being probably formed from the lime-molecule of the original oligoclase. In the same area grits rich in epidote and chlorite (the Green Beds) are converted into hornblende-schists, that are only distinguishable with difficulty from hornblende-schists of igneous origin.

WEATHERING

THERE is in the zone of weathering a great variety of materials : loose mechanical accumulations, rocks of organic and chemical origin, igneous rocks, and the cemented and metamorphosed derivatives of all of these. Since the physical conditions under which these rocks occur are also very variable, the chemical reactions by which they become altered are of a complex character.

The work of weathering is accomplished by (1) mechanical and (2) chemical agencies. The mechanical work results in *disintegration*, the chemical in *decomposition* and *solution*, the ultimate residual product in both cases being soils.[1]

Mechanical Agencies.—The agents of mechanical work are : (1) the diurnal and other variations of temperature (the *insolation* of Walther)[2] resulting

[1] Treitz, " Was ist Verwitterung ? " *C. R. 1ère Conférence Internationale Agrogéologique*, Budapest, 1909, pp. 131-62.

[2] Walther, " Die Denudation in der Wüste und ihre geologische Bedeutung," *Abhandl. Math.-Phys. Classe Gesell. Wiss.*, Leipsic, vol. xvi, 1891, pp. 448-53 ; also *Das Gesetz der Wüstenbildung*, Berlin, 1900.

in *exfoliation* or surface scaling of rocks ; (2) the expansion of water on freezing resulting in the widening of cracks and fissures.; (3) the mechanical action of the roots of growing plants in promoting disintegration ; (4) the burrowing of animals (earth-worms, ants, termites, rabbits, and moles) ; (5) the influence of man by soil cultivation and deforestation.

Chemical Agencies. — The chemical agents are gases, aqueous solutions, and organic compounds. The gases are those contained in the atmosphere, oxygen and carbon dioxide being the most potent. The aqueous solutions are those of the gases oxygen and carbonic acid, and of compounds of the alkalies, alkaline earths and iron and alumina, together with such acids as carbonic, hydrochloric, nitric, and sulphuric. Among organic agencies the chemical work of plants is of the greatest importance, since, as is well known, they are able to extract carbon dioxide and nitrogen from the air, and to fix these gases in the form of carbohydrates and proteids. On the death of the plants the combined carbon and combined nitrogen are, through the influence of bacterial agents, oxidised through many intermediate stages to carbonic and nitric acid. Bacteria act in many other ways : for instance, they are instrumental in the decomposition of iron sulphides, and in the breaking up of iron carbonates with oxidation of the iron. Further reference to these processes will be made later.

Animals also perform an important function in

the process of weathering. Thus the frequent passage of soil through the alimentary canals of earth-worms has a considerable influence on its solubility, and an enormous quantity of vegetable matter is introduced into the soil, for bacteria to work on, by the subterranean labours of ants and termites.[1]

As already stated on page 326, the chief chemical processes that take place in weathering are oxidation, carbonation, and hydration.

Oxidation.—The oxidation of the organic matter provided by plant-decay has already been referred to. The first products are organic acids of the humic group. By a further process of bacterial oxidation these are broken down, the ultimate products being carbon dioxide and water. The decay of plants therefore results in a great concentration of carbon dioxide in the belt of weathering, and material is thus provided for the further process of carbonation.[2] In the same way complex nitrogenous compounds give place to ammonia, nitrites, and nitrates, each stage of the decomposition being the work of a special group of bacterial agents. In tropical regions, where bacteria are more abundant and more active than in temperate

[1] Branner, " The Decomposition of Rocks in Brazil," *Bull. Geol. Soc. Amer.*, vol. vii, 1896, p. 297. See also Passarge, *Die Kalahari*, Berlin, 1904.

[2] Boussingault and Lewy have shown that in a temperate climate the air contained by a soil rich in humus may contain more than 100 times as much CO_2 as atmospheric air, and Struve has shown that the carbonation of the silicates is much greater in regions of abundant vegetation than in those of sparse vegetation (*Pogg. Ann.*, vol. vii, p. 341).

regions, the production of nitrates in the soil is very
large, amounting, it is said, in the valley of the Orinoco
to as much as 30 per cent. of the soil. The greater
proportion of the nitrates thus formed is carried
away in solution by water ; but in rainless regions
(*e.g.* in the pampas of Chile and Peru) they accumulate
in the soil and are exploited for nitre (saltpetre) and
nitratine (Chile saltpetre).

Among inorganic compounds that become oxi-
dised in the belt of weathering, the most important
are those of iron. Considerable quantities of iron
exist in the form of sulphides (*e.g.* pyrites, marcasite,
and pyrrhotite), and ferrous oxide occurs largely in
silicates and carbonates. The oxidation of these
compounds produces hæmatite, magnetite, and, where
the oxidation is accompanied by hydration—as is
mostly the case—limonite, goethite, and turgite.

Concurrently with the oxidation of the iron, the
sulphur of iron sulphides is attacked, producing
various sulph‑acids, the ultimate product being
sulphuric acid, which in the presence of alumina
and alkalies gives rise to the alums, and in the presence
of lime to gypsum. An explanation is thus afforded
of the origin of alum-shales and of crystals of gypsum
in marly clays.

The compounds of other metals such as man-
ganese, copper, zinc, lead, that undergo oxidation in
the belt of weathering, are subordinate in quantity,
but of great importance in the arts. The oxidised
compounds of these metals found in those portions

of their lodes or veins that are within the belt of
weathering, often constitute the richest and most
profitable parts of the mines by which they are ex-
ploited. The actual outcrop of lodes containing
much pyrites is, however, frequently formed by a
limonite or hæmatite gossan (*chapeau de fer*) from
which the valuable metals have been leached out and
carried down to the zone of " secondary enrichment,"
as in the case of the copper deposits of Rio Tinto in
southern Spain.

Carbonation.—As explained on page 161, the pro-
cess of carbonation consists mainly in the substitu-
tion of carbonic for silicic acid in the silicates. It
has been shown experimentally [1] that carbon dioxide
in aqueous solution is capable of attacking many
minerals, such as felspars, hornblende, olivine, and
muscovite, at ordinary temperatures and pressures.
The carbonates of the alkalies and alkaline earths
thus formed are removed in solution and become
potent agents for further desilication; for it is well
known, as a result of Bischof's [2] experiments, that
the alkaline carbonates are capable of decomposing
many silicates at ordinary temperatures and pressures.
A large proportion of the soluble carbonates ultimately
find their way to the sea and are there precipitated
through organic agencies, giving rise to the carbonate

[1] Mueller, " Untersuchungen über die Einwirkung des kohlen-
säurehaltigen Wassers auf einige Mineralien und Gesteine,"
Tschermak's Min. Mittheil., vol. vii, 1897, pp. 25-48.

[2] Bischof, *Elements of Chemical and Physical Geology*, London,
1854, vol. i, pp. 8-11.

sediments that form the basis of the great limestone and dolomite formations of the world. In dry regions, however, the alkaline carbonates may accumulate to such an extent in the soil as to check the growth of vegetation and to produce deserts.

The process of the carbonation of the silicates is accompanied by the liberation of silica, which either remains behind as quartz or goes into solution as colloidal silicic acid,[1] being, in the latter case, largely carried by the ground-water to the belt of cementation and there precipitated.

Hydration.—Next to carbonation this is the most important chemical reaction that takes place in the belt of weathering. It consists in the replacement of the anhydrous silicates and oxides, in the rocks exposed to its influence, by hydrated minerals, such as the members of the kaolin, serpentine-talc, chlorite, and zeolite groups among the silicates, and gibbsite ($Al_2O_3 . 3H_2O$), diaspore ($Al_2O_3 . H_2O$), goethite ($Fe_2O_3 . H_2O$), turgite ($2Fe_2O_3 . H_2O$) and limonite ($Fe_2O_3 + nH_2O$) among the oxides, and gypsum ($CaSO_4 . 2H_2O$) among the sulphates.

The chemical reaction of hydration involves expansion of volume and great liberation of heat. An important corollary of the first-named of these two phenomena is the fact that hydration can only take place where there is room for expansion. It follows that where the rocks are porous, hydration

[1] Kahlenberg and Lincoln, *Journ. Phys. Chem.*, vol. ii, 1898, pp. 77-90.

may proceed down to a great depth, but where they are dense and compact, it is limited to the neighbourhood of the surface, where the weight of the cover is not too great to be overcome by the lifting force of expansion.

Solution and Deposition.—Concurrently with, and partly as a result of, the chemical processes of oxidation, carbonation, and hydration, a considerable amount of mineral matter goes into solution. All minerals are soluble to some extent, even in pure water, the amount dissolved being controlled by the factors— temperature, pressure, and time (see p. 296). But, as already explained, the solvent action of the vadose waters is largely increased by the presence in them of organic acids, carbonic acid, nitric acid, and sulphuric acid, and of their salts, especially the alkaline carbonates.

Mr. Mellard Reade [1] has made an interesting calculation of the amount of salts annually removed in solution from a square mile of the earth's surface. He finds that this amounts on the average to 96 tons of material, divided as follows :

	Tons.
Calcium carbonate	50
Calcium sulphate	20
Sodium chloride	8
Silica	7
Alkaline carbonates and sulphates. . .	6
Magnesium carbonate.	4
Oxide of iron	1

[1] Reade, *Chemical Denudation in Relation to Geological Time*, London, 1879.

The removal of the soluble constituents of rocks effects an increase of the open spaces in them in those cases where the weathered product has sufficient strength to hold together. The limestones are a good example, for in consequence of the solvent action of the ground-water they are often abundantly traversed by open fissures and channels and frequently contain caves.

Not all of the dissolved material, however, is carried away to the sea : wherever evaporation can take place, deposition results. Thus carbonate of lime is deposited as calcite in veins and geodes, and in tropical and semi-tropical countries as tufa, calc-sinter, travertine or " kunkar " in caves or on the surface : stalactites and stalagmites are a characteristic feature of those limestone caves in which there is a sufficient current of air to promote evaporation. Silica is precipitated from solution under similar conditions, as quartz, opal, or chalcedony. Hydrated oxides of iron, aluminium, and manganese are also abundantly precipitated in the belt of weathering from solutions of their carbonates and sulphates.

The deposition of mineral matter from solution may also result through the agency of plants or bacterial life. Thus the precipitation of carbonate of lime is effected by certain bog-mosses and fresh-water algæ. Other forms of algæ precipitate gelatinous silica ; while others again are instrumental in the throwing down of hydrated oxide of iron, as in the case of the so-called lake-ores of Sweden, which, according to

Ehrenberg, Sjögren, and others, result particularly from the work of the diatom *Gaillonella ferruginea*. The formation of kunkar (carbonate of lime) and of laterite (hydrated oxides of iron and alumina) has also been ascribed to the influence of bacteria.[1]

The End-products of Weathering.—The belt of weathering is the source of the materials of which the whole of the sedimentary rocks, including those formed by chemical precipitation and by the aid of organisms, are built up. We may divide these end-products into two classes, viz. (1) those that formed a portion of the original rock and may therefore be termed *original* minerals ; and (2) those that have been produced by the chemical process of weathering, or *secondary* minerals.

The first of these classes can be divided into two groups, viz. those minerals that remain behind in the weathered rock, and may therefore be termed *residual*, and those that are removed by mechanical transportation in running water. The second class, viz. the secondary minerals, may be further subdivided into those relatively insoluble and those soluble in water under ordinary temperatures and pressures. The bulk of the insoluble secondary minerals remain *in situ*, and are therefore residual. Of the soluble minerals a portion is deposited *in situ* and the remainder removed in solution. We have therefore four groups of derivatives, viz.—

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[1] Holland, " The Constitution, Origin, and Dehydration of Laterite," *Geol. Mag.*, 1903, p. 59.

CLASSIFICATION OF THE END-PRODUCTS OF WEATHERING.

ORIGINAL MINERALS $\begin{cases} \text{Residual.}^1 \\ \text{Removed in solution or by mechani-} \\ \quad \text{cal transportation.} \end{cases}$

SECONDARY MINERALS $\begin{cases} \text{Insoluble and therefore residual.}^1 \\ \text{Soluble} \begin{cases} \text{Deposited } in\ situ. \\ \text{Removed in solution.} \end{cases} \end{cases}$

Of the original minerals that escape destruction by weathering, quartz is the most common; and consequently this mineral constitutes the bulk of the mechanical sediments and of the residual materials. Among silicates the felspars are the most important; and fragments of original felspar are a frequent constituent of the sedimentary rocks, especially in the so-called arkòses, which are derived directly from the disintegration of granite. Much mica also escapes destruction; and members of the muscovite group are common in the sedimentary rocks, especially in the clays and shales. Members of the pyroxene-amphibole group are less common, because more easily decomposed. There are also a number of silicates that are very resistant to destruction by weathering, and are therefore found universally distributed among the sediments, but not in great quantity, because they do not occur in great abundance in the original rocks. Such minerals are the following : garnet, staurolite, tourmaline, sillimanite, and kyanite. Resistant minerals, other than silicates, that are of

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[1] For this residual material, which, as shown, consists partly of original, partly of secondary material, the term *Eluvium*, suggested by Trautschold, is largely used, especially by foreign geologists.

common occurrence in the sediments are—the iron-ores, magnetite, hæmatite, ilmenite, chromite ; rutile, zircon, and, with much more localised distribution, diamond, cassiterite, corundum, monazite, xenotime, gold, and platinum.

The insoluble secondary minerals comprise a great variety of silicates. They may be arranged in the following groups : the kaolin-lithomarge group, the serpentine-talc group, the chlorite group, the hydro-mica group, the zeolite group, and the epidote group. There are also the oxides and the carbonates, the former including the gibbsite-corundum group, the quartz group, and the ferric iron and manganese group. The soluble secondary minerals are the carbonates, sulphates, nitrates, and chlorides of the alkalies and alkaline earths.

Residual Deposits or Eluvium.—The residual deposits attain their greatest development in those countries that have remained unsubmerged for a vast period of time : where the weathered products have neither been pared off by glacial erosion nor the solid rocks protected by a covering of glacial or other superficial accumulations. Under especially favourable conditions of climate and topographic relief, disintegration and chemical alteration may extend to many hundred feet below the surface, and the solid rock be replaced in the whole of this zone by soft decomposition products that bear no likeness to their parent, although certain original structures, such as bedding and foliation, may be retained. Deep

weathering of this nature is well seen, for instance, in Brazil,[1] in India,[2] and in Africa.[3]

The materials composing the bulk of the residual deposits are, as we have already seen, gravel, quartz-sand, and clay or lithomarge (an amorphous hydrated aluminium silicate, having the composition of kaolinite, viz., $2H_2O \cdot Al_2O_3 \cdot 2SiO_2$); and more exceptionally the mixture of hydrated oxides known as *laterite*. The degree of admixture of these materials is mainly determined by the composition of the rock from which the deposit was formed. Thus a sandstone or quartzite, by the removal of its siliceous or calcareous cement, disintegrates into a loose aggregate of quartz-sand usually coloured more or less deeply by oxide of iron. On the other hand, rocks containing a large proportion of felspar give rise to a lithomargic clay, which in its purest form is white ("pot clay"), but may be grey, blue, yellow, brown, or black, according to the nature and quantity of the contained impurity; while loams, composed of sand and clay in approximately equal proportions, are derived from rocks, which, besides quartz, contain felspar or other aluminous silicates.

Kunkar.—Under special climatic conditions carbonate of lime derived mainly from lime-felspars is deposited either *in situ* or not far removed from its place of origin. For this process it is necessary

[1] Branner, *Bull. Geol. Soc. Amer.*, vol. vii, 1896, pp. 295-300.
[2] Holland, *loc. cit.*, p. 64.
[3] Hatch, "Conglomerates of the Witwatersrand," in *Types of Ore Deposits*, 1911, p. 202.

that periods of desiccation should alternate with periods of saturation; the ground-water is then brought to the surface by capillarity and deposits in the soil-layer, immediately below the humus, a portion of its carbonate burden as nodules, which are known by their Indian name of *kunkar*.[1] In some cases the carbonate of lime is even deposited along cracks and joints in the rock itself, so that as decomposition progresses the whole weathered portion (of a basic dolerite, for instance) may be gradually replaced, with the result that there appears to be an actual passage from igneous rock to limestone.[2]

Residual Dolomite and Phosphate of Lime.—The removal of carbonate of lime in solution from an impure limestone or from dolomitic limestones results in various residual products. The lesser solubility of dolomite as compared with calcite in dolomitic limestone causes the former to remain behind. Thus the weathering of the limestone of the Paris basin produces a dolomitic sand in which occur nodules of unaltered limestone, locally known as *têtes de chat*. Another instance is furnished by the valuable deposits of almost pure phosphate of lime, left behind in the brown phosphatic chalk in Mons in Belgium by the leaching out of the carbonate of lime by meteoric waters charged with carbonic acid.[3]

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[1] See Passarge, *Die Kalahari*, Berlin, 1904.
[2] For an interesting example of this change, see Hatch, *Report on Mines and Mineral Resources of Natal* (1910), p. 95.
[3] Cornet, " On the Upper Cretaceous Series and the Phosphatic Beds in the Neighbourhood of Mons," *Quart. Journ. Geol. Soc.*, vol. xlii, 1886, p. 325.

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Terra Rossa.—A characteristic residual deposit of limestone is the red ferruginous earth, or " terra rossa," which covers the surface of large areas in south-eastern Europe on the borders of the Adriatic (the Karst of Istria and Dalmatia).[1] Although the limestones of this region are often snow-white, the fact that they contain a small amount of red ferruginous clay can be shown by dissolving a large sample in weak acetic acid. The " terra rossa " is therefore the insoluble residue of the limestone that remains after the removal of the carbonate by weathering. Such residual red clays are found overlying limestones in every part of the world where the climatic and topographic conditions are suitable for their accumulation ; but they are not found in regions of heavy rainfall, where the material is washed away as soon as it is formed. In the latter districts, however, a material of similar composition collects in swallow-holes and on the floor of caves, into which it is swept by the run-off from the rainfall.

Clay-with-Flints.—This name was given by W. Whitaker to a reddish-brown clay containing many unworn flints as well as broken angular flints and some pebbles, which is found spread over the surface of the Chalk in the South of England. The *argile à silex* of the Paris basin is a similar deposit. The clay-with-flints was considered by Whitaker and others [2] to be

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[1] See Neumayr, *Verhandl. Geol. Reichsanst.*, 1875, p. 50.

[2] " Geology of London," *Geol. Surv.*, vol. i, 1889, p. 281 ; and Darwin, *The Formation of Vegetable Mould*, 1881, pp. 138, 139.

a residual deposit formed by the solution of the Chalk and the accumulation of its contained flints and clay. The fact, however, that the proportion of clay is more than could possibly be accounted for on any theory of solution, and the further fact that clay-with-flints contains a large percentage of rounded quartz grains not derivable from the Chalk, has caused subsequent observers [1] to regard it as largely derived from the overlying Eocene (Reading beds) ; in other words, as probably a mixture of a residual deposit, formed by solution from the Chalk, with a worked-up material from remnants of denuded Tertiary beds. Still more recently it has been suggested that the detritus derived from the Chalk and from the Eocene outliers, that had accumulated by the atmospheric waste of ages, was in Glacial times swept up by an ice-sheet, coming from the north or north-west, and so produced the compound mass known as Clay-with-flints.[2] The glacial theory of the origin of this material is applied by its authors to the deposit occurring north of the Thames in Buckinghamshire, Berkshire, Hertfordshire, and Middlesex, and is not claimed by them to be applicable to deposits of the same name in other districts.

Laterite.[3]—Among the residual products of rock-

[1] Clement Reid, " Explanation of Sheet 208," *Mem. Geol. Surv.*, 1903, p. 64. " Geology of the Country around Dorchester," *Mem. Geol. Surv.*, 1899, p. 37. Jukes-Browne, *Quart. Journ. Geol. Soc.*, vol. lxii, 1906, p. 132.

[2] Sherlock and Noble," Glacial Origin of the Clay-with-Flints of Buckinghamshire," *Quart. Journ. Geol. Soc.*, vol. lxviii, 1912, p. 202.

[3] Although often a derivative of igneous rocks, laterite is not confined to these (see p. 342).

weathering, in tropical and semi-tropical countries, is the material known as laterite, to which attention was first directed by Buchanan. In giving it this name [1] he referred to the employment of laterite in India for the manufacture of bricks, in which use is made of its property of hardening on exposure. It has since been found to occur in many other countries, such as the Malay Peninsula, the Dutch East Indies, South America, and East, West, and South Africa ; in fact, it appears to be one of the commonest residual products of ferruginous and aluminous rocks under suitable climatic conditions. Distinction is made by. the Indian geologists [2] between " high-level " and " low-level " laterite, the former being a true residual material, and the latter mainly a detrital accumulation consisting of transported pebbles and quartz-sand, cemented by lateritic material.[3] We shall confine ourselves, however, to the consideration of the true residual laterite, merely remarking that since there is no *a priori* reason why this residual material should not be equally well formed at low levels as at high levels, the distinction between high-level and low-level laterite seems to be quite unnecessary and indeed confusing.

A great number of analyses of laterite have clearly established the fact that it consists to a large extent

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[1] From *later*, the Latin for brick. Buchanan, *Journey from Madras through Mysore, Canara, and Malabar*, London, 1807, vol. ii, p. 440.

[2] Oldham, *Geology of India*, 2nd edition, p. 373.

[3] Dr. Leigh Fermor purposes to call these detrital laterites " lateritite," *Geol. Mag.*, 1911, p. 514.

of a hydrated mixture of oxides of iron, aluminium, titanium, and manganese :[1] *e.g.* hæmatite (Fe_2O_3), turgite ($2Fe_2O_3 . H_2O$), goethite ($Fe_2O_3 . H_2O$), limonite ($Fe_2O_3 + nH_2O$), etc., gibbsite ($Al_2O_3 . 3H_2O$), diaspore ($Al_2O_3 . H_2O$), and pyrolusite, psilomelane, or wad (all oxides of manganese). The ratio between the iron oxides and the aluminium oxides varies to any extent, so that laterites may approximate, on the one hand, to high-grade iron-ores, and on the other to almost pure bauxite.[2] When manganese is present it usually occurs in nodular concretions of psilomelane, wad, or pyrolusite, which are sometimes sufficiently abundant to constitute an ore of manganese. Mixed with these oxides in varying proportion are a lithomargic clay and quartz-sand.[3]

[1] H. Warth and F. J. Warth, " The Composition of Indian Laterite," *Geol. Mag.*, 1903, p. 154. These analyses show that the water is chiefly present in combination with the aluminium oxide, the iron oxide being mostly present in the anhydrous or slightly hydrated condition (hæmatite or turgite). The mean of eight analyses of Indian " high-level " laterites " implies anhydrous ferric oxide and a mixture of 93.5 per cent. gibbsite and 6.5 per cent. diaspore." It would appear from this that dehydration had already set in. Compare Holland, *Geol. Mag.*, 1903, p. 65.

[2] According to Holland a mixture of gibbsite and diaspore (*Rec. Geol. Survey, India*, vol. xxxii, p. 176). Lacroix (in *Minéralogie de la France et de ses colonies*, p. 342) calls it a " rock " consisting of a mixture of various hydro-oxides of aluminium and iron with clay and sandy impurities.

[3] Dr. Leigh Fermor suggests that true laterite should be defined as a residual material containing from 90 to 100 per cent. of these " lateritic constituents." Where the percentage of the latter is only from 50 to 90 per cent., he suggests that the material should be described as " lithomargic laterite " when the diluting material is mainly clay, and as " quartzose laterite " when the diluting material is mainly quartz-sand (*Geol. Mag.*, 1911, p. 514).

One of the most striking features of laterite is its colour, which is dominantly red or brown. It is not, however, uniform in this respect, being often mottled or streaky. Moreover, it frequently contains whitish patches of a soft aluminous material from which the iron oxide has been withdrawn by segregation. A local concentration of the latter produces nodular concretions of iron oxides, and similarly manganese when present is concentrated in nests or black botryoidal aggregates.

Most laterites are traversed by numerous small anastomosing tubes, generally lined with limonite and often filled with clay. The removal of the softer material at the exposed surfaces has frequently produced a vesicular or cavernous structure, and this, combined with its hardness and dark colour, has often led to laterite being mistaken for lava.

A brecciated variety is produced by the collapse of the first-formed superficial crust and a subsequent recementing of the broken fragments by iron oxides.

With regard to the origin of laterite, there has been much discussion and considerable divergence of opinion ; but all are agreed that it may result from the decomposition of a great variety of rocks, whether of igneous, sedimentary, or metamorphic origin. Most of the Indian laterite is found overlying the vast area of the Deccan basalts ; but it is also found resting on gneiss and other rocks of the Peninsula. In West Africa [1] it is found on schists,

[1] Campbell, *Trans. Inst. Min. and Met.*, vol. xix, 1910, p. 432.

in East Africa on volcanic rocks and on gneiss,[1] and in South Africa [2] on slate, sandstone, and granite.

Although not entirely confined to the tropics, laterite is conspicuously developed under tropical conditions : that is to say, a warm, humid climate, although apparently not absolutely essential, certainly favours its production ; and an alternation of wet and dry seasons appears to be essential. The occurrence of laterite has been observed in temperate latitudes and at temperate altitudes ; but it does not occur where there is a prolonged winter. To account for the decomposition of the silicates of alumina and iron to laterite instead of to clay (lithomarge or kaolin) under the special climatic conditions mentioned, several theories have been formulated. Thus some authors [3] consider that laterite is the direct result of the alteration of ferro-aluminous silicates in place ; while Sir Thomas Holland [4] goes a step farther and suggests that it " is due to the agency of lowly organisms, possibly akin to the so-called nitrifying bacteria. With these there are probably forms akin to the bacteria which oxidise and fix ferrous compounds, and which, precipitating the silica in the colloid form,

[1] Maufe, "Report relating to the Geology of the East Africa Protectorate," *Colonial Reports*, No. 45, 1908.

[2] Rogers and Du Toit, *Geology of Cape Colony*, p. 391.

[3] Bauer, " Beiträge zur Geologie der Seychelles," *Neues Jahrbuch für Min.*, 1898, vol. ii, p. 163. Harrison, " The Residual Earths of British Guiana termed ' Laterite,' " *Geol. Mag.*, 1910, p. 439. Fermor, *Geol. Mag.*, 1911, p. 514.

[4] *Geol. Mag.*, 1903, p. 59. See also Chauteard and Lemoine, *Comptes Rendus Acad. Sci.*, vol. cxlvi, pp. 239-42, and *Bull. Soc. de l'Indust. Min. St. Étienne*, 1909, pp. 1-37.

permit its removal by the dilute alkaline solutions simultaneously formed." Other writers,[1] however, consider laterite to be a metasomatic replacement of rock, decomposed *in situ*, by a hydrated mixture of oxides obtained from the underlying rock by the action of the ground-water and brought to the surface, during periods of desiccation, by capillarity, aided perhaps by the rootlets of forest trees.   E. S. Simpson[2] regards it as a true efflorescence, *i.e.* a deposition on the surface of the rocks of substances brought from below by capillarity.

Bauxitic Clays.—These clays contain more alumina than is necessary to supply the demands of the whole of the silica present for the formation of the kaolinite molecule.   The fine state of division of the material makes it impossible to determine the nature of the mineral in which the excess alumina exists.   In Ayrshire such rocks have been shown by G. V. Wilson to have been derived by the action of carbonated alkaline waters on a basalt with the assistance of rapid changes in the saturation level of the ground water, due to the seasonal alternation of periods of desiccation and intense humidity.[3]

[1] Broughton, *Journ. Asiatic Soc., Bombay*, vol. v, 1857, p. 639. De Lapparent, *Traité de géologie*, p. 1611. Hislop, *Journ. Asiatic Soc., Bombay*, vol. v, 1857, p. 63. De Bois, *Tschermak's Min. und Pet. Mit.*, 1903. Maclaren, *Geol. Mag.*, 1906, p. 536. Campbell, *Trans. Inst. Min. and Met.*, vol. xix, 1910, p. 432.
[2] Simpson, " Laterite in Western Australia," *Geol. Mag.*, 1912, p. 400. Walther, *Zeits. Deutschen Geol. Ges.*, vol. lxvii, 1915, p. 113.
[3] G. V. Wilson, "The Ayrshire Bauxitic Clay," *Mem. Geol. Surv. Scot.*, 1922.

The Iron Ores of Lake Superior.—These ores are now considered to be residual deposits. The iron-bearing rocks here form part of a metamorphic mass of pre-Cambrian age, forming the southern part of the great Canadian shield. This series is in part sedimentary, in part volcanic, and invaded by intrusions of several different ages. The primary iron-bearing rocks, which occur at several different stratigraphical horizons, were originally ferruginous cherts, consisting of mixtures of silica and green iron silicates in varying proportions. According to Van Hise and Leith[1] the ore has been concentrated in the iron formation by the leaching out of silica by meteoric waters. The largest concentrations of iron ores are found where impervious beds have been folded into synclines ; here and there, however, as in the Mesabi region, the reason for the concentration is not obvious. The origin of the iron in the primary rocks is rather obscure: it is now believed to be of magmatic origin, derived from solutions poured out into the sea during the eruption of the basic volcanic rocks that compose part of the series : its concentration is undoubtedly a process of metasomatic replacement by iron compounds in solution.

Soils.—Since, as already stated, soils are the ultimate product of rock-weathering and often accumulate *in situ*, they are (with the exception of those that have originated by water-transportation, or are

[1] Van Hise and Leith, " The Geology of the Lake Superior Region," *Monograph* 52, *U.S. Geol. Survey*, 1911. Leith, *The Economic Aspects of Geology*, New York, n.d., p. 167.

wind-blown) residual deposits. They consist con-
sequently of the debris of original minerals and of
the re-deposited secondary minerals formed from
them, together with the humus, which is a direct
product of the bacterial decay of vegetable and animal
matter.[1]   A large proportion of the secondary mineral
matter consists of the finely-divided amorphous
material to which agricultural chemists apply the
term " clay."   One of the characteristics of this clay
is that it possesses the property of remaining sus-
pended in water for a long time without settling.
Hence it has been compared by Schloesing[2] and
others to colloid substances, such as gelatinous silica,
starch, and gum, which, though they appear to be
dissolved, yet cannot be diffused through a mem-
brane.   Recent researches on colloids show that
they are essentially suspended matter in an ex-
tremely fine state of division.   Also the so-called
" colloid clay " of Schloesing consists of ultra-
microscopic solid particles, probably to a large extent
of the hydrated silicates of aluminium to which the
names lithomarge and halloysite have been applied.[3]

[1] On soil production as a result of weathering, consult Van
Bemmelen, " Beiträge zur Kenntniss der Verwitterungsprodukte
der Silikate in Ton-, vulkanischen und Laterit-böden," *Zeits.
für anorg. Chem.*, vol. xlii, 1904, p. 265 ; also (by the same author)
" Die Verwitterung der Tonböden," *Zeits. für anorg. Chemie*,
vol. lxii, 1909, pp. 221-36.

[2] *Comptes Rendus de l'Académie des Sciences*, 1878, p. 376.

[3] Mellor and Holdcroft, " The Chemical Constitution of the
Kaolinite Molecule," *Trans. Eng. Cer. Soc.*, vol. x, 1911, consider
that the essential constituent of clay—" clayite," as they term it
—is not a hydrated aluminium silicate, but an alumino-silicic
acid, the salts of which are the zeolites.

Ramann[1] uses the term "kaolin jelly" for this matter.

The mineral constituents of soils that are of sufficient size to be identified by the usual optical methods are essentially the same as those found in sand. All the ordinary rock-forming minerals occur, but the more stable, such as quartz and white mica, predominate; while the heavy and resistant minerals of the igneous and metamorphic rocks, such as tourmaline, kyanite, staurolite, garnet, and zircon, are widely distributed and abundant. Clay soils are, owing to their impermeability to percolation, comparatively rich in soluble mineral salts, such as the sulphates and chlorides of sodium, magnesium, and calcium. In arid climates, where there is a deficient rainfall and great evaporation, such salts tend to accumulate and produce the so-called *alkali-soils*. Sodium carbonate also occurs in soils to a small extent; but since this salt has a strong influence on the properties of soils, American writers have used its presence or absence to divide the saline soils into two groups, namely, *white alkali-soils*, with sodium and magnesium sulphates and sodium chloride; and *black alkali-* or *soda-soils*, with sodium carbonate. Another and perhaps a better usage is to call the chloride soils *saline* and the alkaline carbonate soils *alkaline*. Gypsum, the hydrated sulphate of lime, is present in most clay soils, and is the chief source of supply for the sulphur required by plants. The sulphuric acid necessary for the

[1] Ramann, *Bodenkunde*, 3rd edition, Berlin, 1911, p. 245.

formation of this mineral is produced by the oxidation of pyrites, which, in a finely-divided state, is widely distributed through many clays, to which it imparts their characteristic dark-blue colour.

The phosphoric acid, which is present in soils in combination with calcium, iron, and aluminium, and is so important for the growth of vegetation, is derived, in the first place, partly from the mineral apatite (a chloro- and fluo-phosphate of calcium), a frequent constituent of the igneous rocks ; partly from the amorphous mineral phosphates (phosphorite and coprolites) that are formed by the segregation and concentration in many argillaceous rocks of phosphatic material of organic origin, *e.g.* the hard and bony parts of fish, fish excrements, etc. (see p. 221).

The most characteristic constituents of soils are perhaps the oxides and hydrated compounds of iron ; and it is due to the presence of these ferric oxides and ferric hydrates that most soils are coloured yellow, brown, or red, no matter what the rocks from which they are derived. Some soils also contain numerous particles of manganese oxides. These are either of residual origin, having been derived mechanically from rocks whose destruction by weathering has given rise to the soil, or the manganese is precipitated by the oxidising influence of the air from percolating solutions in which it exists as a bicarbonate.

The most important constituent of soils, however, from the point of view of fertility, is the humus which is accumulated in the soil by the bacterial decay of

vegetable and animal matter. It has two important functions : (1) it provides plant food in a readily available form ; and (2) it gives rise, by certain further bacterial processes, to organic acids which play an important part in the decomposition of the mineral constituents of the soil. Many of the complex chemical processes that are brought about in the soil by the aid of micro-organisms have been investigated and the functions of the various organisms have been studied with a considerable degree of success ; but the subject is still obscure and is beyond the scope of this book. The action of the nitrifying bacteria (*Nitrobacter*) in producing nitrates in the soil has already been alluded to on page 327. One further example of such bacterial action may be quoted. By the aid of certain bacterial organisms (Winogradsky's *iron bacteria*) [1] the hydrated oxides of iron (limonite, etc.) of the soil are reduced to the ferrous state and combine with carbonic acid, present in the water of the soil, to form a soluble bicarbonate of iron. On exposure to air a reoxidation takes place and the iron is precipitated as " bog iron " or " iron pan." A continuous layer of this " pan," which in drier climates is represented by a kind of " crow-stone " gravel (the " *oude-klip* " of the South African Boers), consequently tends to form below insufficiently-drained clayey and peaty soils.

By agricultural investigators the constituents of

[1] Winogradsky, " Über Eisenbakterien," *Botanische Zeitung*, 1888, p. 260.

the soil are generally ranged under five heads, viz. sand, silt, clay, lime, and humus.

From this point of view soils, then, consist of sand, silt, clay, calcium carbonate,[1] and humus in varying proportions, and the practical soil classification of agriculturists is based on the predominance of one or other of these constituents. Sandy or " light " soils are those in which sand is dominant ; " loamy " soils contain approximately equal proportions of sand and clay ; in clayey or " heavy " soils finely-divided argillaceous material is the principal constituent ; in calcareous soil calcium carbonate predominates ; while soils rich in humus are termed peaty.

The work of Sibirzew,[2] Glinka, and other Russian and German observers has shown that the character of the soil depends largely on the climate, and that under similar climatic conditions very similar soil-

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[1] The term " lime," as applied to the calcareous constituents of a soil, although in universal use, is objectionable, because the substance in question is invariably calcium carbonate, not the oxide or hydrate. Almost equally bad is " chalk," which is sometimes applied in the same sense, since this has a definite stratigraphical meaning.

For a general account of the properties of soils and the methods of examination employed, reference should be made to Hall, *The Soil*, 2nd edition, London, 1910. For an admirable account of the detailed investigation of a particular region, see Hall and Russell, *Report on the Agriculture and Soils of Kent, Surrey, and Sussex*, published by the Board of Agriculture and Fisheries, London, 1911.

[2] Sibirzew, " Étude des sols de la Russie," *Congr. Géol. Internat.*, St. Petersburg, 1899, pp. 73-125. Ramann, *Bodenkunde*, 3rd edition, p. 559. Glinka, *Die Typen der Bodenbildung*, Berlin, 1914 (a German translation of the author's Russian lectures).

types can be produced from widely different materials, accumulated in various ways ; while, on the other hand, similar materials under different climatic conditions yield very different soils. The most important factors in this connection are the relation between rainfall and evaporation, temperature and the influence of vegetation. The following are instances of residual soils whose formation is dominated by climatic conditions.

Black Cotton Soil.—The black cotton soil, which is known as the Regur in British India, occurs in tropical and semi-tropical countries where wet and dry seasons alternate. It is a black argillaceous clay, consisting of very finely-divided material which is very retentive of moisture and is plastic when wet. In the dry season it becomes friable and shrinks greatly, its surface being then seamed with cracks. As a rule, it is found in open swampy plains, where the substratum is impervious and the under-drainage is so imperfect as to cause a water-logging of the soil at the end of the rainy season. In consequence of this a large proportion of the water can only escape by evaporation at the surface, to which it is drawn by capillarity. During this process the less soluble carbonate of lime is deposited as concretions (*kunkar*) at or near the base of the black cotton soil, while the more soluble alkaline salts accumulate in its upper portion, to which they impart a slightly alkaline character (the " sour veld " of South Africa). Most of these alkaline salts, however, are carried down-

ward by the first rains of the next wet season, and this movement carries the humus from the surface and distributes it through the soil, and is therefore indirectly responsible for its characteristic black colour.[1]

The Tchernozom or "Black Earth" of Russia is another example of a soil extraordinarily rich in humus ; it averages 10 per cent. and occasionally rises to 16 per cent. Its origin has been the subject of much controversy ; Dokutchaiev concludes that it always shows a close genetic relationship to the underlying rocks and is not, as formerly believed, a transported marine or glacial deposit. It can be formed from a great variety of rocks, especially loess, chalk, Jurassic clays, or granite, and its peculiar characters are attributed directly to extensive growth of vegetation, especially grass, in a region of small rainfall.[2]

Podzol is a soil covering enormous areas in the colder parts of Russia and Siberia. It is pale grey in colour, and very siliceous, owing to the leaching out of most of the soluble constituents, including the iron and phosphoric acid. These dissolved constituents are often reprecipitated some distance below the surface as a hard layer or "pan." Similar bleached sandy soils are often found in heather-covered tracts in western Europe, and in the drier.

[1] Maufe, *Report relating to the Geology of the East Africa Protectorate*, 1908, p. 56.

[2] Kossowitsch, *Die Schwarzerde*, Vienna, 1912 (a German translation of a Russian work).

parts of eastern ·England : they are usually very·
barren. Some Russian varieties have a high salt-
content and are then known as saline podzol.

Saline Soils, or Solontzy, are largely developed in
the south-east of Russia and in Turkestan, where they
are also known as Byelozom or White Earth. The soil
is generally black above and grey below, and the
surface is sometimes covered by a layer of salt crystals,
especially chlorides and sulphates of sodium, mag-
nesium, and calcium. Soils of this type are character-
istic of the southern dry steppes, where the annual
rainfall is 8 inches or less.[1]

[1] For a general classification of soil-types, see Rastall, *Agri-
cultural Geology*, Cambridge, 1916, chap. vi.

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